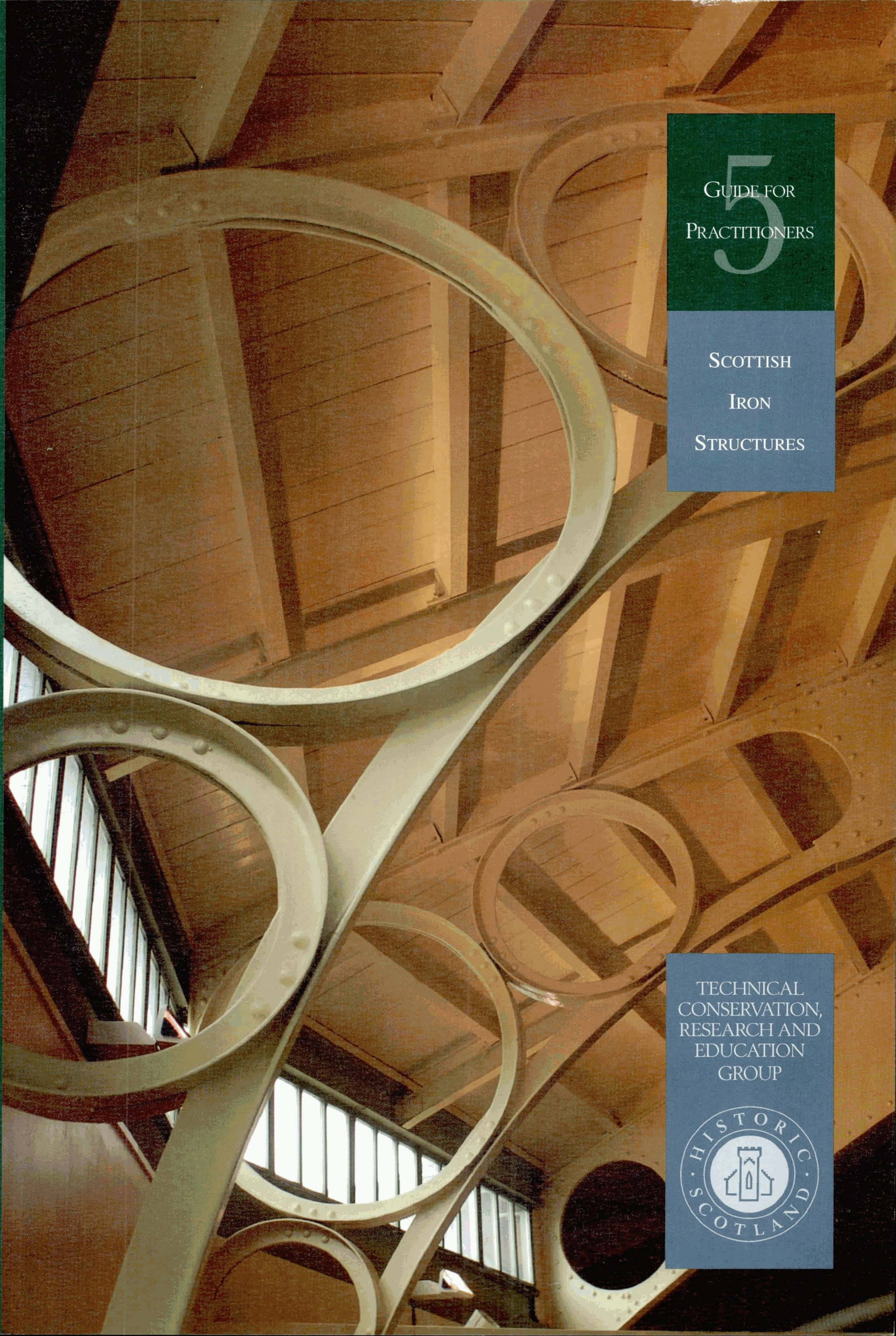

Guide for Practitioners 5

Scottish Iron Structures

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5

GUIDE FOR PRACTITIONERS

SCOTTISH IRON STRUCTURES

by
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of Historic Scotland

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CONTENTS

LIST OF ILLUSTRATIONS

Scottish Events	Year	International Events
First charcoal fired blast furnaces	c.1600	*Sweden the main producer of iron*
Founding introduced by John Meikle for casting cannon etc	c.1686	
	1701	Neviansk ironworks, Urals, Russia
	1709	Smelting iron with coke, at Coalbrookdale
James Watt, b. Greenock	1736	
	1740	Steelmaking: Huntsman's crucible casting process
Bonawe Ironworks established	1753	
Thomas Telford, b. Langholm	1757	
Carron Company established	1759	
John Rennie, b. Phantassie, East Lothian	1761	
Water-powered furnace blowing engine at Carron by Smeaton	1764	
Iron rails cast at Coalbrookdale laid into the Carron Works	1767	
Steam engine, James Watt's first patent	1769	
David Mushet, b. Dalkeith; Robert Stevenson, b. Glasgow.	1772	
Carron Company granted Royal Charter by George III	1773	
	1776	First Boulton & Watt steam engine
Wilsontown Iron Works started (closed 1842)	1779	Iron Bridge, Coalbrookdale
	1783	Profiled rolls for wrought iron; Henry Cort's patent
	1784	Puddling process for wrought iron: Henry Cort's patent
Bell Mill, Stanley, Perthshire	1786	Charles Gasgoine leaves Carron for Russia
William Fairbairn, b. Kelso	1789	
James Beaumont Neilson b. Shettleston	1792	The first 'fireproof' mill; Strutt's Derby Cotton Mill
	1794	Telford's Pont Cyssylte Aqueduct, Llangollen Canal
	1796	First coke-fired iron works in central Europe: Gliwice
	1797	The first iron-framed mill; Ditherington, Shrewsbury
Stevenson proposes a cast iron framed light for the Bell Rock	1799	
James Braidwood, b. Edinburgh	1800	
Blackband ironstone discovered by David Mushet	1801	
Joseph Mitchell, b. Forres	1803	Pont des Arts, Paris (demolished 1980)
Earliest iron-framed mill?: Houldsworth's Mill, Glasgow	1805	
Broadford Works, Aberdeen: James Nasmyth, b. Edinburgh	1808	
Cast iron rails; Kilmarnock & Troon Railway	1811	Bourse~& Halle au Ble domes, Paris (1809-13)
Craigellachie Bridge, (Thomas Telford)	1814	St. Georges's Church, Everton, Liverpool
Union Suspension Bridge, Scottish Borders (Samuel Brown)	1820	
The Great Fire of Edinburgh	1824	First iron columns in USA: Theatre, Philadelphia
	1826	Telford's Menai Suspension Bridge
Argyle Arcade, Glasgow (John Baird I)	1827	Collapse of Gray's Cotton Mill, Salford
Hot-blast patent granted to J.B. Neilson	1828	Stockton and Darlington 'Wrought Iron Railway'
Braid Burn Railway Bridge, cast iron girders	1831	'Best form of iron beams', published by Hodgkinson
Cast iron conservatory, Fairfield House, Dalkeith	c.1835	
	1837	Riveting machine, developed by William Fairbairn
William Arrol, b. Houston, Renfrewshire	1839	Steam hammer, invented by James Nasmyth
Lewis Gordon made Professor at Glasgow	1840	'Strength of cast iron pillars' published by Hodgkinson
	1844	Deck beams, uses patented by Kennedy & Vernon
	1847	Dee Railway Bridge disaster, Chester
	1848	The Palm House, Kew (Richard Turner)
Alexander's thread mill, Duke St. Glasgow	1849	Royal Commission report on the use of iron in bridges
Walter MacFarlane & Co.'s Saracen Foundry established	1850	Britannia and Conway wrought iron tubular bridges
	1851	The Great Exhibition Building, London
The Old Fruitmarket, Glasgow, fully iron-framed	1854	
W.J.M. Rankine appointed to Chair at Glasgow	1855	Oxford Museum
Gardner's Store completed, Jamaica St, Glasgow	1856	Steelmaking: Bessemer process patented
Bessemer process trials at William Dixon's works fail	1857	First Otis elevator, New York
Findhorn Railway Viaduct; William Fairbairn tubular girders	1858	
David Kirkaldy's tests on iron and steel for Robert Napier	1859	Robert Stephenson and Isambard Kingdom Brunel die
	1860	The Boat Store, Sheerness: fully iron-framed
	1861	James Braidwood dies in the Tooley Street fire
	1862	Steel beams used in a Lombard St. building, London
Ballindalloch and Carron Bridges over the River Spey	1863	Leeds Corn Exchange
	1867	Steelmaking: Siemens process patented
Siemens Steel plant built by the Steel Company of Scotland	1874	
Tay Railway Bridge disaster	1879	Steelmaking: the Basic process patented
Train Shed, Glasgow Queen Street	c.1880	Steel beams rolled by Bolckow, Vaughan & Co.
Steel beams rolled at David Colville & sons Dalzell Works	c.1884	
Basic steel plants established at Glengarnock and Wishaw	1885	Home Insurance Building, Chicago
New Tay Railway Bridge	1887	
Ferguslie and Anchor Mills, Paisley: steel beams	1889	Tour Eiffel and Galerie des Machines, Paris
Magdalen Green Bandstand, Dundee	1889	
Forth Railway Bridge, in steel	1890	
Building Regulations in Glasgow cover structural iron	1892	
Jenner's Building, Edinburgh, riveted angle steel columns	c.1895	Wrought iron joists last rolled
The Scotsman Building, Edinburgh: steel-framed	1902	

FOREWORD

Iron forms the basis of many of Scotland's most important and significant historic structures, from the skeletons of great mills to the fabric of bandstands or the intricate details adding character to our Victorian buildings. Understanding this material is therefore crucial to our efforts to preserve that heritage. This Guide provides a comprehensive overview of the historic uses of iron in a construction context.

The Guide begins with the history of iron and its use in Scotland, from the earliest manufacturers to the great producers in their heyday, before detailing how the start of steel production signalled a decline in the use of cast and wrought iron as a building material. It offers a detailed discussion on the structural uses of iron in factories, engineering workshops and residential buildings, and considers the construction of bridges and glasshouses. This helps place iron in its proper context and demonstrates how intrinsic it is to the construction of our diverse built heritage. In so doing, it offers a better understanding of the material and of the significance of its impact.

The Guide then considers the engineering properties of both wrought and cast iron, including the metallurgy and performance of the different materials. This is complemented by a detailed discussion of iron as a structural material, and its use in cast and wrought beams, columns and struts. For each element, factors such as manufacture, strength and assessment are examined, concluding with an examination of the load resistance of different floor structures and their resistance to fire or collapse. Finally, appropriate conservation needs, including repair, strengthening and corrosion prevention, are considered. These sections are vital for gaining a detailed knowledge of the behaviour of buildings that use iron. In turn, they allow us to better appreciate the issues surrounding their effective care, maintenance and conservation.

Each section in the Guide complements the other to produce a volume that extends our understanding of a material that is an integral part of Scotland's past. It is anticipated that its publication will greatly assist practitioners in ensuring that structures

Ingval Maxwell OBE
Director, Technical Conservation Research and Education
Edinburgh
March 2006

Illustration 1 (opposite) An Iron Time Line

Illustration 2 Foreground: Magdalen Green Bandstand, Dundee (1889)
Background: The Tay Railway Bridge (1887)
Constructed by William Arrol & Co., designed by the civil engineers W.H. Barlow & Son.
The bridge was a replacement for Scotland's best known structural failure - the high girders over the navigation spans of Sir Thomas Bouch's first bridge blew down in a gale on 28th December 1879, as a train crossed, killing all on board. (Picture: D Mitchell)

1 INTRODUCTION

1.1 Aims

To provide guidance on good conservation practice for those concerned with iron in Scottish buildings, with emphasis on structural aspects.

To give an historical overview of the structural use of iron in Scotland.

1.2 Scope

The focus of this guide is principally on iron in buildings, but it is hoped that it will also be of interest and useful to bridge engineers.

Examples of the conservation and repair of decorative or 'architectural' ironwork are included to illustrate techniques that may be applicable to structural iron.

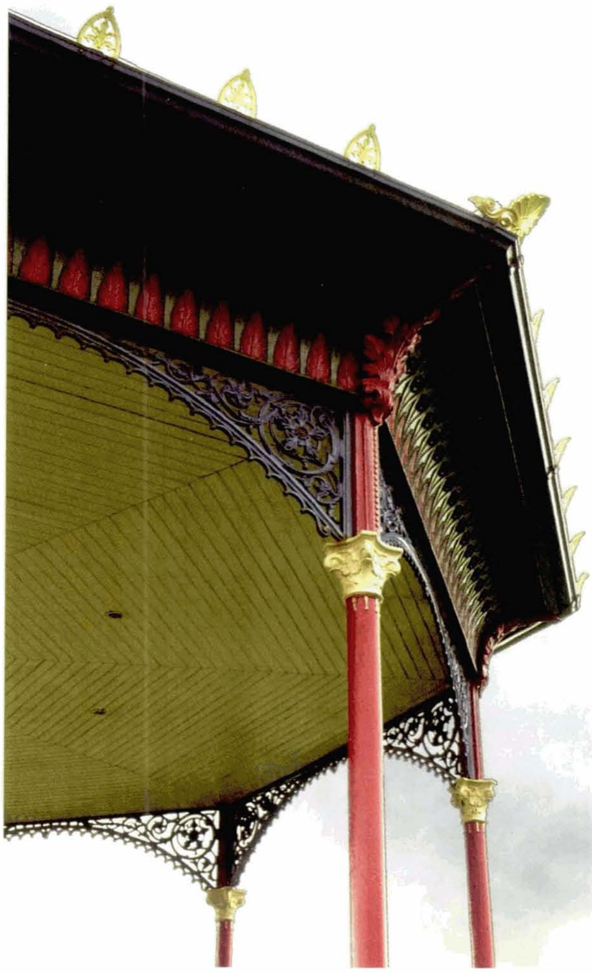


Illustration 3 Magdalen Green Bandstand, Dundee Detail 1 (Picture: D Mitchell)

Illustration 4 Magdalen Green Bandstand, Dundee Detail 2 (Picture: D Mitchell)

Architectural cast iron from the Saracen Foundry of Walter MacFarlane & Co. Dundee City Architect's Department oversaw conservation in 1990, with some replacement castings by Alyth Foundry.

1.3 Iron

1.3.1 Iron

PURE IRON

- Over 5% of the earth's crust is iron, one of the most common and useful metallic elements
- Chemical symbol Fe (from the Latin ferrum)
- Atomic number 26, atomic weight 55.85, valence 2+ or 3+
- Density 7870 kg/m^3
- Melting point 1539°C
- A good heat conductor. Thermal conductivity at room temperature of 80.2 W/m °C
- A good electrical conductor. Electrical resistivity at 0°C of $9.710 \times 10^{-8}\,\Omega$ m
- Extremely high magnetic susceptibility in its common forms

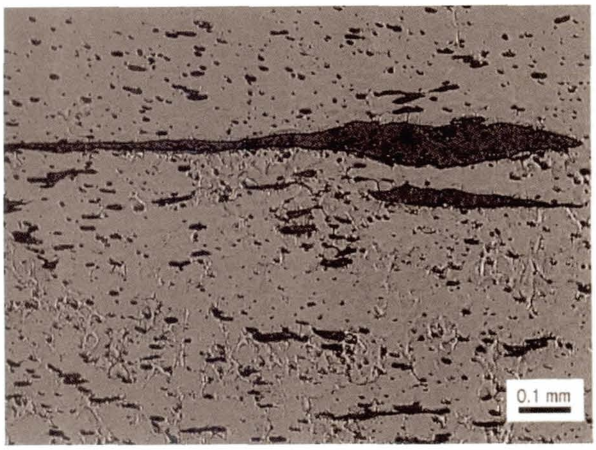


Illustration 6 Wrought iron microstructure. Polished and acid-etched 'ferritic' wrought iron, viewed through a metallurgical microscope (Picture: Mike Broadhurst, CAPCIS Ltd)

1.3.2 Wrought iron

Early metal objects were cast in bronze, a relatively soft alloy of copper and tin. 'The Iron Age' in Scotland began around 750BC with the coming of the Celts, who brought with them superior tools and weapons of wrought iron. The new material was strong and hard compared to bronze and could be hammered and ground to give a sharp, durable cutting edge. As iron in almost pure form, wrought iron is a ductile material. It has similar mechanical properties to modern mild steel, which is iron alloyed with around 0.2% carbon. Though less uniform, with a fibrous structure rather like wood, wrought iron has advantages over steel in terms of its workability at the blacksmith's forge and resistance to corrosion (Illustrations 5 and 6).

Illustration 7 Cast iron fracture. A 1 1/4 inch (31mm) thick cast iron plate, part sawn through then broken to show a grey, crystalline fracture (Picture: T. Swailes)

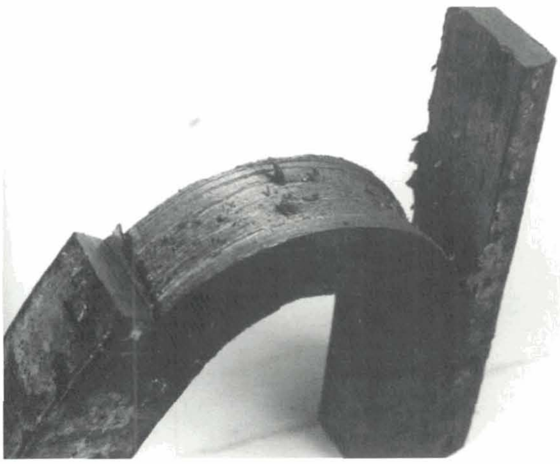


Illustration 5 Wrought iron fracture A 1 inch (25.4mm) square bar, notched to one third depth with a hacksaw and then cold bent in a vice to show the fibrous structure of the material (Picture: T. Swailes)

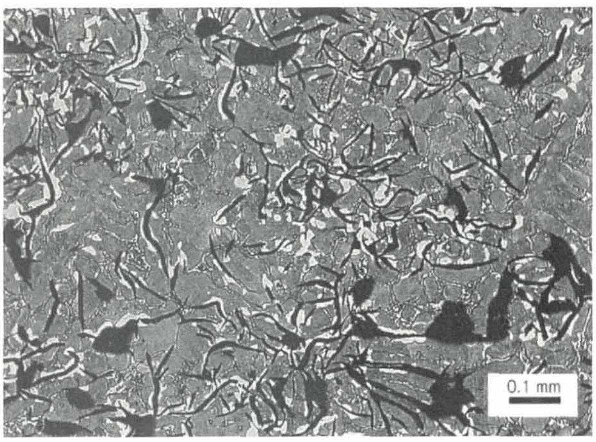


Illustration 8 Cast iron microstructure. A polished and acid-etched cast iron surface, viewed through a metallurgical microscope.
In metallurgical terms, a very uniform pearlitic grey cast iron, with little or no ferrite present, and with a near-continuous phosphide eutectic
(Picture: Mike Broadhurst, CAPCIS Ltd)

1.3.3 *Cast iron*

If early man had by accident heated iron to melting point, the resultant casting would have been rejected as too brittle for the manufacture of tools and weapons. This relative brittleness is due to a high carbon content, usually around 4%. In 'grey' iron, a significant proportion of the carbon is present in the form of graphite flakes, giving a fresh break a characteristic grey, crystalline appearance (Illustrations 7 and 8). Although not forgeable, and brittle and weak in tension compared to wrought iron, cast iron is very strong in compression, can be cast into intricate shapes, and is very durable. When technological advances enabled cast iron to be produced relatively cheaply and in large quantities, it quickly became a valuable structural material.

Illustration 9 Part of a cylinder for an early steam engine (1766) Cylinders for James Watt were cast at the Carron Works, but they proved unsatisfactory. Early Carron workmanship lacked the necessary precision and it was left to John Wilkinson of Shropshire to perfect the art of casting and boring engine cylinders in the 1770s (Barker, 1992). (Picture: 'The Story of Carron Company, 1759-1959').

1.4 Structural iron - the Scottish tradition

The industrial revolution in Scotland is considered by many to have begun in 1759 with the creation, on an unprecedented scale, of the first integrated coke-fired ironworks at Carron (Illustration 9). Scottish ores were particularly suitable for making fine castings and the Carron Works established a reputation for Scottish decorative cast iron that was to last well into the twentieth century. With Carron a notable exception, the iron industry in Scotland developed much later in Scotland than in England and Wales. The civil engineer Thomas Telford, for example, relied in the early nineteenth century on the expertise of the North Wales foundry of William Hazledine for sound structural castings (Illustration 10). From the early 1830s, production in Scotland increased enormously and Scottish iron gained a strong foothold in the British market. The keys to this success, besides the natural business acumen of the Scots, were the development of the 'hot-blast' by James Beaumont Neilson of the Clyde Ironworks and the exploitation of the 'blackband' ores of Lanarkshire and Ayrshire.

People have long been a significant Scottish export. In the eighteenth century, Carron expertise in cast iron and ironworking was taken to Russia by Charles

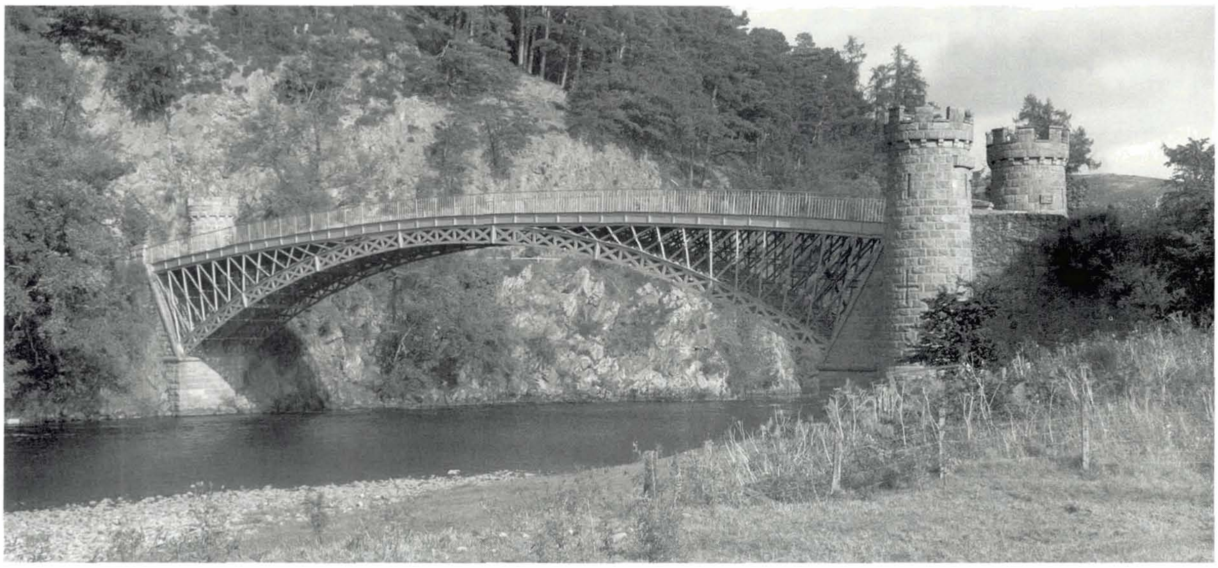


Illustration 10 Craigellachie Bridge (1812-15) The ironwork for Thomas Telford's bridge, now a Scheduled Ancient Monument, was cast by William Hazledine. Telford's foreman, William Stuttle, supervised erection of the structure over the River Spey. The bridge was reconstructed in steelwork above the arch ribs in 1964 and by-passed eight years later. Cast iron plaques bearing the legends "CAST AT PLAS KYNASTON RUABON DENBEIGHSHIRE" and "1814" have been retained. (Picture: RCAHMS)

Illustration 11 Moulding cast iron letter boxes at Ballantine Bo'ness Iron Company Ltd, Links Road, Bo'ness, West Lothian in 2000 (Picture: T. Swailes)

Gascoigne and to Poland by John Baildon. Much of the fine structural and decorative ironwork of those countries can therefore be said to have Scottish ancestry. In the nineteenth century the not very Russian-sounding Baird Works, near St. Petersburg, established a formidable reputation. Scotland also had close links with France, where William Playfair went to establish mills for rolling wrought iron. Overseas markets were exploited extensively by the later architectural ironworks of Glasgow (e.g. Saracen Foundry), Kirkintilloch (e.g. Sun Foundry) and Falkirk. As far afield as Brazil and Australia much of the architectural ironwork is in fact Scottish and, in Britain, iron 'street furniture', from post boxes to lamp posts was, and still is, very often cast in Scotland (Illustrations 11 and 12).

In factory buildings, iron first appeared in power transmission systems and machinery. Internal structural framing of cast iron, used in England in 1797, was in 1804 and 1807 being employed in the first 'fireproof' cotton and flax spinning mills in Scotland. More than a century apart and very different in scale, Broadford Works in Aberdeen contains two flax mills, built in 1808 and 1914, that are recognisably similar pre-fabricated kits of cast iron columns and beams. Such building systems appeared elsewhere in Western Europe only in the second half of the nineteenth century and were little used for factories in America, where 'slow-burning' timber construction was preferred. Several early cast iron bridges and building frames were shipped in kit form to Scotland from England and Wales, but within a few decades, there

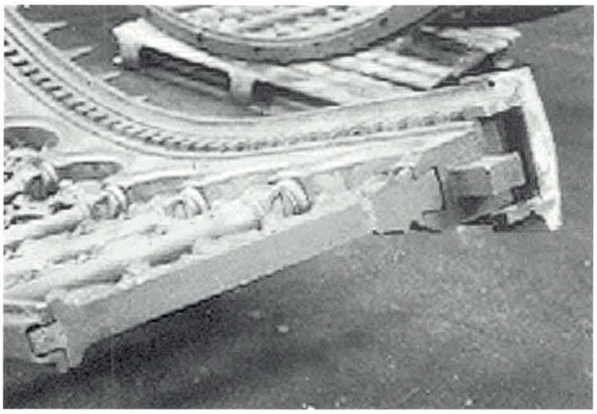


Illustration 12 Cast iron railings undergoing refurbishment at Ballantine Bo'ness Iron Company Ltd, Links Road, Bo'ness, West Lothian in 2000. Note the dovetail connections (Picture: T. Swailes)

was also a considerable traffic in the other direction. The rapid construction in London's Hyde Park of the vast pre-fabricated Crystal Palace for the Great Exhibition of 1851 captured the imagination of Scottish ironfounders, and the Old Fruitmarket in Glasgow is an early 'descendant' of that building (Illustrations 13 and 14).

Hidden behind the façades and within the floors of Scottish public and commercial buildings, and even in private houses, cast iron is to be found to a surprising extent (Illustrations 15 and 16). In towns and cities throughout Scotland, shop fronts and lintels to upper floors that might elsewhere in Britain or Europe be timber are found to be cast iron. Occasionally the entire façade is of iron. Glasgow in particular has some fine examples with innovative iron frames and floor systems behind, contemporary with iron buildings in New York by James Bogardus. In 1892, well ahead of London, Glasgow introduced regulations concerned with the strength of iron in buildings. Scotland's distinctive architecture is rightly celebrated, but many Scottish buildings also occupy an important place in the history of the development of modern structural framing systems. This aspect of their character deserves recognition and requires careful conservation.

Fine decorative work in wrought iron came to England via French pattern books and craftsmen in the early seventeenth century, but Scotland has very few examples of the art. The raw materials for early wrought iron were often imported from Sweden or Russia. The chemical properties of Scottish ores, in particular their relatively high phosphorous content, made them very suitable for castings, but not very suitable for conversion into good wrought iron. Perhaps partly because of this, Scotland was never self-sufficient in structural wrought iron. The girders of Thomas Bouch's ill-fated Tay Bridge of 1879, for example, included wrought iron from Middlesbrough (Illustrations 17 and 18). Another factor important later in the nineteenth century was the heavy consumption of home-produced material by the Clyde shipbuilders and heavy engineering industries. From about 1855 to 1890 in commercial and industrial buildings, wrought iron 'boiler-plate girders' and bressummers supporting walls are found, but probably not to the same extent in Scotland as in London, where built up beams and girders were used extensively (Illustration 19).

Scottish ores proved unsuitable for making early Bessemer steel, but after using open-hearth mild steel for the construction of the Forth Bridge between 1882 and 1890, William Arrol & Co. erected a large number of steel-framed engineering workshops. Following closely behind developments in England, steel beams on cast iron columns were used in two Paisley cotton mills built in 1886-9 and in many city centre commercial buildings over the following 25 years. In Scotland, as in England, the use of steel in high rise buildings trailed the United States. The steel-framed

Illustration 13 The Old Fruitmarket, Glasgow. Ironwork Detail (Picture: M. Watson, Historic Scotland)

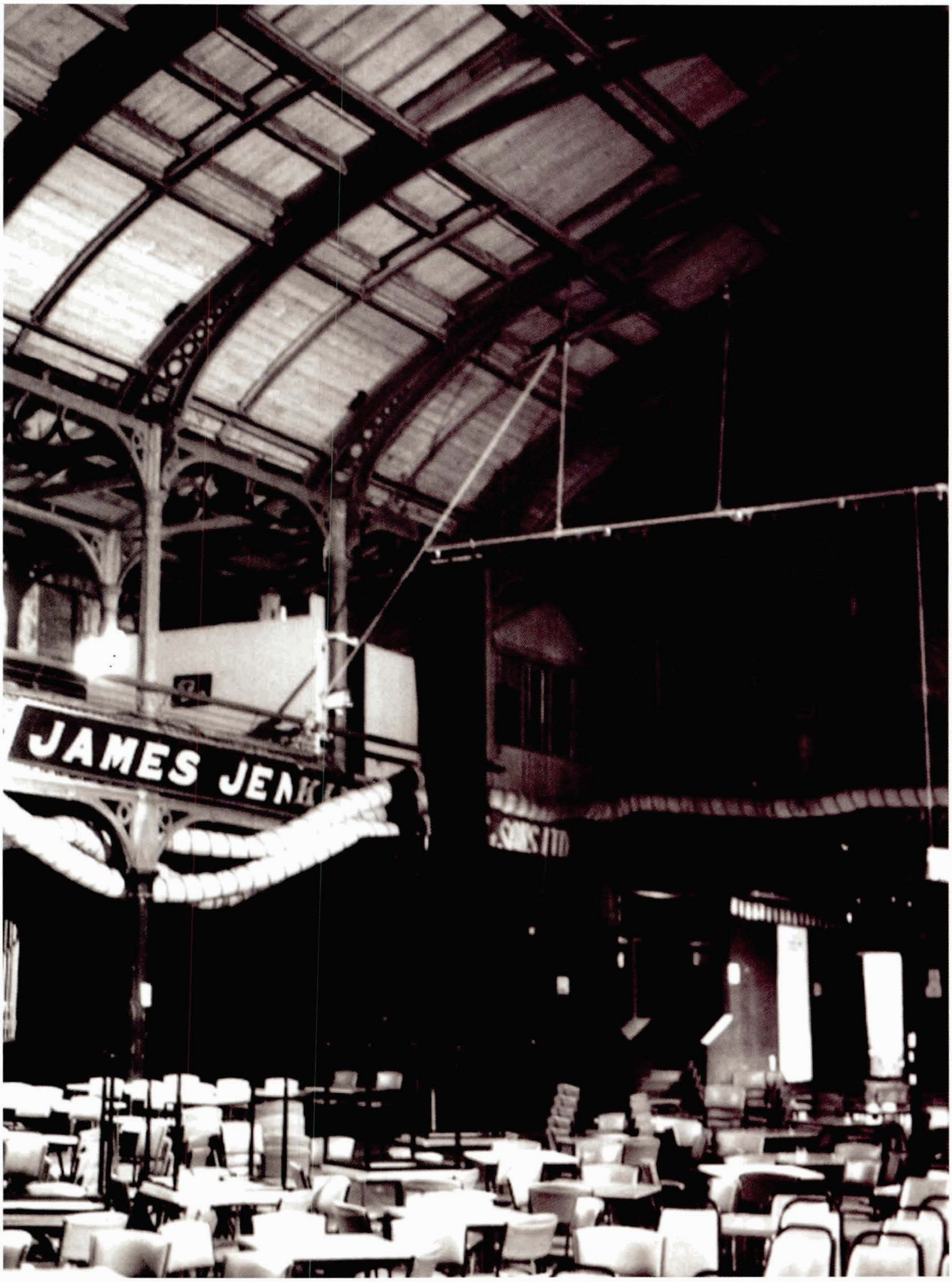
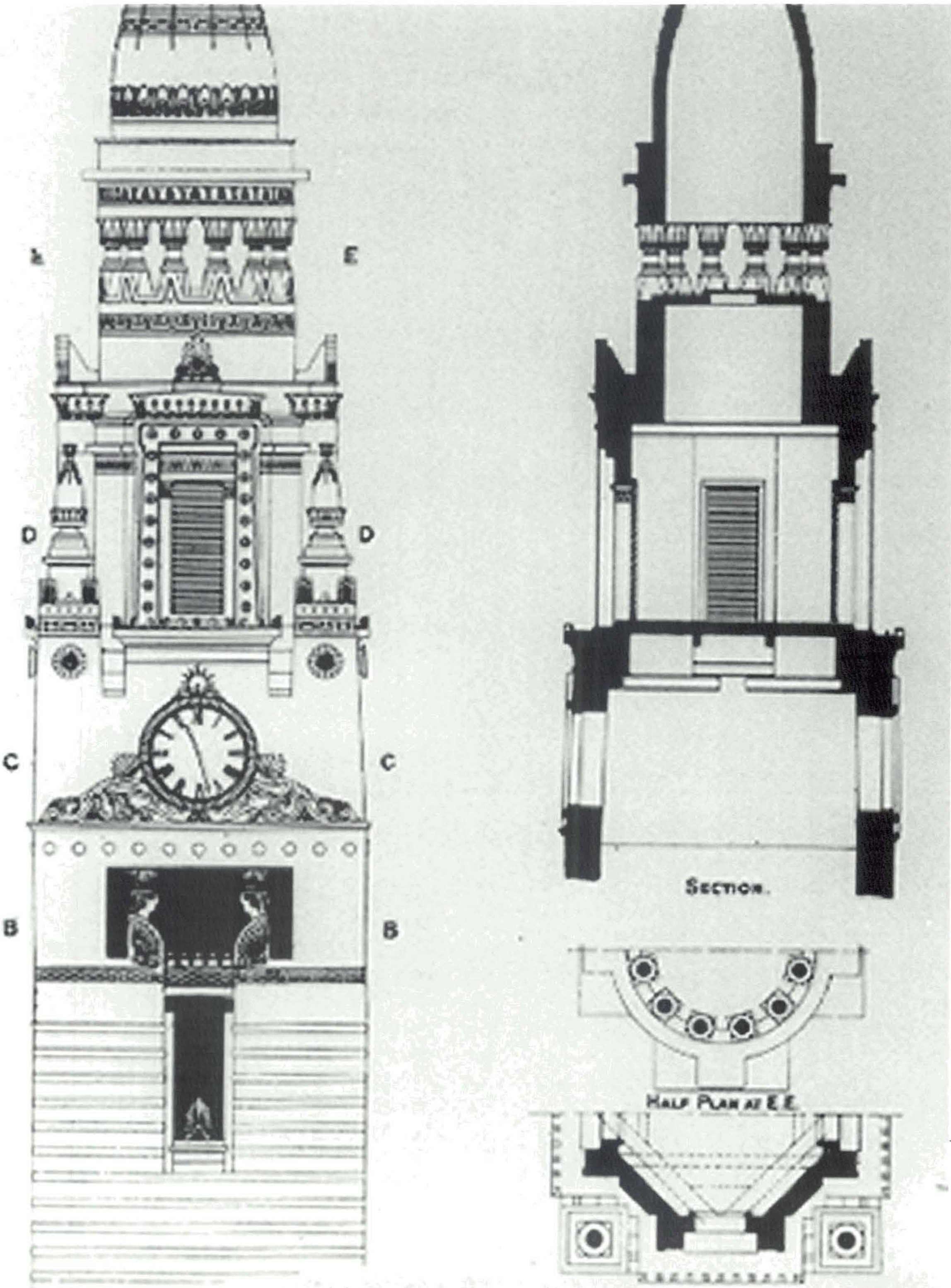


Illustration 14 The Old Fruitmarket, Glasgow (1852-4) Interior
In February 1852, Robertson & Lister submitted a tender in the sum of £4,028-4s-1d for "covering over that part of the Bazaar property to the North of City Hall" (Corporation of Glasgow Minute Book C2·14·3). The main hall and its galleried side aisles are reminiscent of the building erected in London's Hyde Park in 1851 for the 'Great Exhibition'. By the summer of 1854, Lister and Robertson had not quite completed the work, and the Council had understandably complained about slow progress. The Glasgow Directory of 1845 lists "Robertson & Lister (successors to Bankier & MacKenzie), smiths, engineers, millwrights and iron roof constructors, Victoria Works, 79 Mitchell Street". The last entry for the firm, in 1856, described them simply as "iron-house builders" (Picture: T. Swailes)



internal corbelling with cast iron supports

internal corbelling with cast iron supports

Illustration 15 St. Vincent Street Church, Glasgow (1857-9) Modern record drawing extract
Cast iron beams were used as lintels to internal corbelling in the church tower by the architect Alexander 'Greek' Thomson. Thomson specified cast iron where his contemporaries would generally not have done so. For example, accounts of three of Thomson's villas include descriptions of cast iron lintels over openings of modest span ('Villa & Cottage Architecture', Blackie & Sons, 1863). Recently, during conservation of Holmwood House (1857-8), the last of these three villas, the lintels were found not to be cast iron as specified, but timber, some in poor condition and requiring attention. Holmwood House is now open as a National Trust for Scotland property (Picture: Jacobs Babtie)

Illustration 16 St. Vincent Street Church, Glasgow Photograph of cast iron lintels to internal corbelling in the tower (Picture: Jacobs Babtie)

Illustration 17 The first Tay Railway Bridge (1879). Detail of flange angle, with a rolling mark partially obscured by rivets to the web. Rolling marks are rare on wrought iron, quite common on rolled steel sections. Possibly the mark is of Hopkins, Gilkes & Co., of Middlesbrough, contractors for the first Tay Railway Bridge (Picture: T. Swailes)

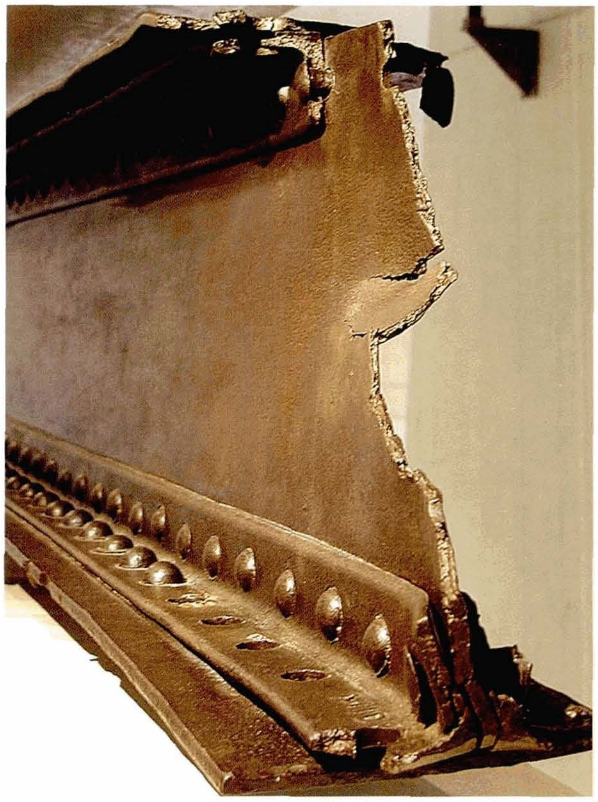


Illustration 18 The first Tay Railway Bridge (1879). A riveted wrought iron girder fragment recovered from the Tay, now in the Museum of Scotland, Edinburgh (Picture: T. Swailes)

and reinforced concrete-framed buildings of the early twentieth century did not totally eclipse cast iron, with characteristic art deco motif cladding panels representing a resurgence in the popularity of the material as late as the 1930s.

During the research for this publication, the many buildings visited have provided examples of iron structures before, during, and after conservation. Usually site visits have been short, and supported by limited historical research, leaving scope for more detailed studies by others. It is hoped that the rich and varied applications of iron in structures presented here will stimulate interest in both the buildings themselves and in the archival material that relates to them.

1.5 General principles and philosophy of conservation

Engineers sometimes have difficulty in proving the structural adequacy of iron-framed structures to their satisfaction, or to the satisfaction of other engineers. There have been some notable 'near misses' in the past, the like of which it is hoped that this publication will help to avoid in the future. Of many suspected instances of the unjustified condemnation of iron structures, three historic structures of great importance may be mentioned. In the 1950s, an engineer's report recommended replacement of the Palm House in London's Kew Gardens with a new structure. In the 1970s, demolition of many of the splendid iron-framed warehouses in the Liverpool's Albert Dock was recommended. More recently, engineers recommended the demolition of Carron Bridge over the River Spey and replacement in steel, with only the outer cast iron ribs to be retained in non-structural façades. Fortunately, good sense and good engineering prevailed, and each of these structures has been saved for present and future generations with *minimum intervention* - a principle that is central to successful conservation work.

Conservation includes all the processes in looking after a place that can help in retaining its cultural

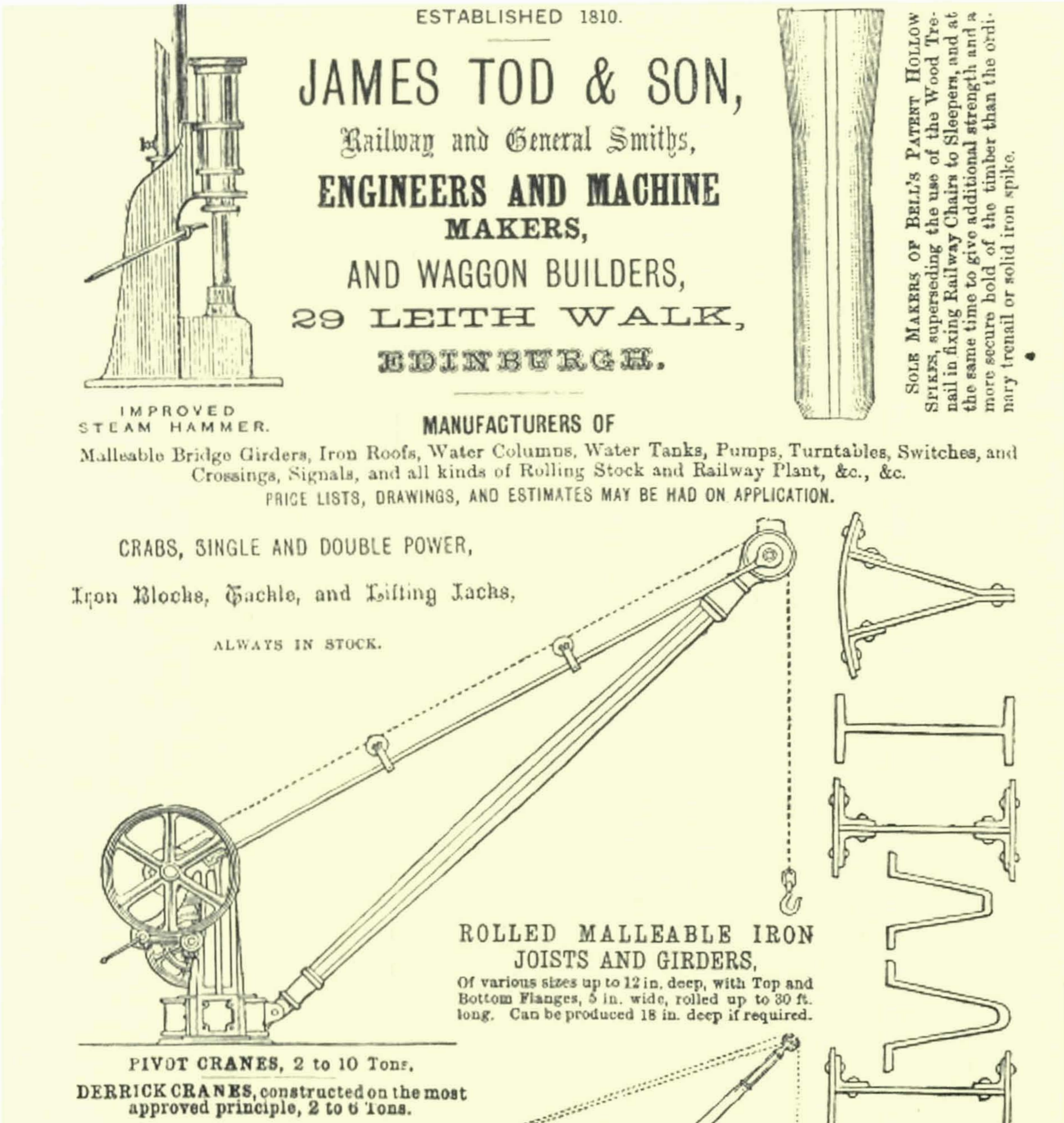


Illustration 19 Edinburgh & Leith Post Office Directory Advertisement, 1868
James Tod & Son (established 1810), Railway and General Smiths, Engineers and Machine Makers, and Waggon Builders, 29 Leith Walk, Edinburgh. Products included 'Rolled Malleable Iron Joists and Girders of various sizes up to 12 in. deep, with Top and Bottom Flanges, 5 in. wide, rolled up to 30 ft. long. Can be produced 18 in. deep if required'

significance. It includes maintenance and may, according to circumstances, include repair and upgrading to suit proposed compatible uses - often it will be a combination of more than one of these. Some key terms referred to here are defined in The Australia ICOMOS Charter for the Conservation of Places of Cultural Significance, known as The Burra Charter, as follows:

- *Cultural significance*

Aesthetic, historic, scientific or social value for past, present or future generations.

- *Maintenance*

The continuous protective care of the fabric, contents, and setting of a place.

(to be distinguished from repair).

- *Repair*

Involves *restoration* (i.e. returning the existing fabric of a place to a known earlier state, e.g. by removing accretions, reassembling existing components etc., without the introduction of new material), or *reconstruction* (i.e. returning a place as nearly as possible to a known state, including the introduction of materials, either new or old, into the fabric). Any repairs should ideally be reversible, preferably using materials that match the originals.

The sensible advice from the British Standards Institution (BS 7913: 1998, *Guide to the principles of the conservation of historic buildings*) in respect of repair and assessment is to follow experience and judgement, on the basis of what has been proved to work. In structural performance terms, subject to certain conditions, on which this Practitioners' Guide gives guidance, there is no reason why an old building that has stood the test of time will not continue to do so, even if proof by calculation is not possible. This publication also addresses some important safety issues applicable to large framed buildings, where the progressive collapse of extensive sections of the building as a result of a single localised structural failure may have to be considered. It must also be recognised that, in common with other building materials, exposed ironwork deteriorates and regular, carefully planned maintenance is essential if structures are not to deteriorate to the point where they become unsafe. Even with very severe deterioration, it is rare for an iron structure to be genuinely 'beyond repair' - a phrase sometimes used by those who would prefer a clear site for redevelopment to an historic building.

The first task in any conservation project should be the preparation of a study of the physical, documentary and any other evidence that sheds light on the past and present condition of the building and on its importance. These findings will inform an assessment of the significance of the site which in turn will determine conservation policy. Preparation of a conservation plan encompasses all these processes (see the leaflet, *A Guide to the Preparation of Conservation Plans*, Historic Scotland 2000 for additional advice, or Kate Clark, *Informed Conservation,* English Heritage, 2001).

1.6 Using this Practitioners' Guide

In addition to the Contents section which provides a comprehensive listing of subsection topics within each Chapter, a full Glossary of technical terms is included for reference. Section 9 contains contact information for organisations that may have relevant technical expertise and also includes details of Internet-based sources, such as CANMORE, the searchable database of the National Monuments Record of Scotland made available through the RCAHMS.

Summary information for each Scottish building and structure referred to in the main text (or illustrated) is presented in tabular form in the Structures Index. The details given include the type of structure, date, location (OS Grid Reference), and where applicable, National Monuments Register of Scotland Number. The References and Further Reading section includes case studies involving the conservation, refurbishment, and repair of iron structures.

A table is provided of old and new units of weights and measures, with conversion factors at Appendix B. Within the main text, where doing so enables sense to be made of the modular and repetitive nature of iron-framed construction, dimensions are given in imperial units (feet and inches and fractions of an inch). Likewise, historic load and stress data is generally presented in the original units, together with the modern equivalent values in brackets.

2 IRON MAKING

2.1 Introduction

This section provides an overview of Scottish iron making and iron working industries and the beginnings of bulk steel making. Several authoritative works have dealt in detail with these and related industries in Scotland, and with what remains of them below and above ground (Butt, 1967; Hume, 1974-7, and 1989; Hay, 1986). An invaluable pocket-sized illustrated gazetteer of Scotland's industrial heritage has also been published (McDonald, 1996). The Journal of the Iron and Steel Institute and the rival contemporary periodicals The Engineer and Engineering are useful sources of information on later nineteenth century iron and steel industries.

2.2 Early iron making

Iron in pre-industrial Scotland was an expensive commodity, used sparingly in buildings for fixings in the form of cramps, ties, straps, bars and nails. The simple smelting methods used enabled only small quantities of the early blacksmith's raw material to be made at one time. A wood fire would be lit in a small furnace a few feet in height and lined with fire-resisting clay, with fragments of iron ore fed in at intervals, together with more fuel. Heat was maintained by using bellows to continuously blow in air at the base of the furnace. After several hours, the furnace would be opened to reveal a spongy lump or 'bloom' of iron and slag at the bottom, weighing little more than a kilogramme. Hard hammering then removed much of the slag and consolidated the iron ready for the smith. Working in wrought iron was important in a number of crafts and the hammermen's guild, active in many seventeenth century Scottish towns, would include wrights, coopers, blacksmiths and masons (Illustration 20).

Illustration 20 The gravestone of a blacksmith hammerman, showing the tools of his trade Larbert Kirkyard, Stirlingshire (Mair, 1988) (Picture: John Donald, Edinburgh)

The common iron ores are oxides of iron. Given sufficient heat and the presence of ore and a reducing agent, a chemical reaction takes place, one product of which is iron:

iron oxide + carbon ➡ Iron + carbon monoxide

(ore) (charcoal)

As wood burns in air it turns to charcoal, a form of carbon, thus providing both heat and the reducing agent. The early furnaces, or 'bloomeries', did not become hot enough to yield a free-flowing molten iron. In any case, if the furnace became too hot, iron in a fully molten state would absorb carbon and the result on cooling would be a small lump of brittle and unworkable cast iron, contaminated with slag.

Iron making on a much larger scale became possible with the introduction of the blast furnace to Britain early in the sixteenth century. An early charcoal-fired blast furnace could produce over a ton of cast iron a day. Most of the early cast iron was converted into wrought iron in a charcoal-fired hearth known as a 'finery'. In the finery, air was blown over the re-heated cast iron, causing the oxygen in the air to combine with the carbon in the iron and reduce it to wrought iron. The wrought iron was then re-heated in the 'chafery', a second charcoal hearth (but without the air blast) to raise it to forging temperature. The buildings housing the finery and the other equipment used in the manufacture of wrought iron were known collectively in the iron trade as 'the forge'.

Ironworks in Scotland

Name	Started	Disused by	County	Shipping port	OS reference
Goatfield/ Crelackan (charcoal)	1775	1813			NN 024 006
Bonawe (charcoal)	1730	1866		via Loch Etive	NN 010 310
Devon	1790	1866	Clackmannanshire	Clackmannan	NS 898 959
Forth			Fife	Alloa	NT 039 862
Lochgelly			Fife	Burntisland	NT 080 880
Lumphinnans			Fife	Burntisland	NT 175 927
Balgonie	1802	1816	Fife		NT 302 990
Carron	1759-63		Stirlingshire	Grangemouth	NS 880 823
Kinniel			Linlithgow	Bo'ness	NS 990 803
Almond			Linlithgow	Bo'ness	NS 962 764
Gladsmuir			Haddingtonshire	Cockenzie	NT 457 733
Garscube			Lanarkshire	Glasgow/ Bowling	NS 540 700
Housel (Househill)	1840's		Renfrewshire		NS 480 640
Govan	1840's		Lanarkshire	Glasgow	NS 590 635
Quarter			Lanarkshire	Glasgow	NS 725 517
Clyde (became part of Colville's)	1785-6		Lanarkshire	Glasgow	NS 660 140
Wishaw			Lanarkshire	Glasgow	NS 805 555
Monkland	1825-6		Lanarkshire	Glasgow	NS 724 637
Gartsherrie	1828		Lanarkshire	Glasgow	NS 722 662
Summerlee	1836		Lanarkshire	Glasgow	NS 728 664
Carnbrae (or Carnbroe)	1840's		Lanarkshire	Glasgow	NS 748 635
Chapel (near Chapelhall)			Lanarkshire		NS 780 628
Calder (near Calderbank)	1805		Lanarkshire	Glasgow	NS 768 628
Castlehill	1840's		Lanarkshire	Glasgow/ Leith	NS 954 756
Dundyvan	1834		Lanarkshire		NS 733 645
Langloan			Lanarkshire	Glasgow	NS 725 645
Coltness	1840's		Lanarkshire	Glasgow/ Leith	NS 795 565
Hareshaw			Lanarkshire		NS 815 605
Shotts (Foundry started 1828)	1802-5		Lanarkshire	Glasgow/ Leith	NS 885 605
Omoa (near Newarthill)	1787	1866	N. Lanarkshire	Glasgow / (Leith?)	NS 795 597
Wilsontown, or Cleugh	1779-86	1842	S. Lanarkshire		NS 950 550
Nithsdale			Ayrshire	Ardrossan/ Troon	unconfirmed
Eglinton			Ayrshire	Ardrossan	NS 307 423
Glengarnock/ Kilbirnie			Ayrshire	Ardrossan/ Glasgow	NS 315 535
Blair	1840's		Ayrshire	Ardrossan	NS 300 490
Lugar			Ayrshire	Ardrossan/ Troon	NS 590 210
Dalmellington			Ayrshire	Ayr	NS 480 060
Portland			Ayrshire	Ardrossan/ Troon	NS 451 369
Muirkirk	1787	1921	Ayrshire	Ardrossan/ Troon	NS 700 270
Ardeer/ Kilwinning			Ayrshire	Ardrossan/ Glasgow	NS 290 425
Galston	1840's		Ayrshire		NS 495 365
Glenbuck (a ruin in 1860)	1795	1813	Ayrshire		NS 746 298
Lancefield (forge)					
Gartness (forge)			Lanarkshire		

Steel plants c.1905

Steel Company of Scotland	Newton and Glasgow
David Colville & Sons	Dalzell
Parkhead Forge	Glasgow
Lanarkshire	Flemington
Clydebridge	Cambuslang
Other	

Illustration 21 Scottish Ironworks

Company late 1840s	Company 1861	Furnaces 1788	1796	1823	1830	1849	1861	Puddling furnaces and wrought iron production 1839
		1	1					
		1	1					
Devon Iron Co.	G and J Miller		2	3	3	1	3	
	Forth Iron Company					5	7	
	Lochgelly Iron Company					2	4	
	Alexander Christie & Co.						1	
Carron Co.	Carron Iron Co.	4	4	5	5	3	4	
	William Wilson & Co.					4	4	
	James Russell & Son.						3	
	C & A Christie						1	
	Wilsons & Co.					1	2	
William Galloway (of Paisley)								
William Dixon	William Dixon					5	6	Wm. Dixon, at Glasgow Iron Works, Town-head, 200 tons/wk
	Colin Dunlop & Co.						2	
(land feud from) James Dunlop	Colin Dunlop & Co.					7	7	
	Robert Bell						2	
Monkland Iron Co.	Monkland Iron & Steel Co.			2	3	9		
William Baird & Co.	William Baird & Co.				1	16	16	
Wilsons & Co.	Wilsons & Co.					6	8	
Alison & Co.	Merry & Cunninghame					6	6	
							3	
William Dixon & Co.	William Dixon			3	4	7	8	
Shotts Iron Co.	Shotts Iron Co.					2	3	
John Wilson	John Wilson trustees					9	8	Dunlop, Wilson & Co., 300 tons/wk
	Robert Addie					6	6	
Henry Houldsworth	Coltness Iron Co.					6	9	
							1	
Shotts Iron Co.	Shotts Iron Co.			1	1	4	5	
Robert Stewart	Robert Stewart		2	2	2	4	4	
William Dixon		2	2	2	2			
	Wilsons & Co.					3	3	
	William Baird & Co.						8	
	Merry & Cunninghame					9	9	
J. M'Donald	William Baird & Co.					6	5	
	Willaim Baird & Co.					4	4	
	Dalmellington Iron Co.					3	5	
	Portland Iron Co.					4	5	
Muirkirk Iron Co.	William Baird & Co.		2	3	3	3	3	Muirkirk Iron Co., (4 blast furnaces), rolling 40-100 tons/ wk
	Merry & Cunninghame					3	4	
M'Allum & Co.								
abandoned. Started by English co.								
								puddling wrought iron from white cast iron, in small quantity
								puddling wrought iron from white cast iron, in small quantity
		30 acid open-hearth furnaces, 1 basic furnace						
		18 acid open-hearth furnaces						
		6 acid open-hearth furnaces						
		8 acid open-hearth furnaces						
		9 acid open-hearth furnaces						
		9 acid open-hearth furnaces						

Illustration 21 (continued)

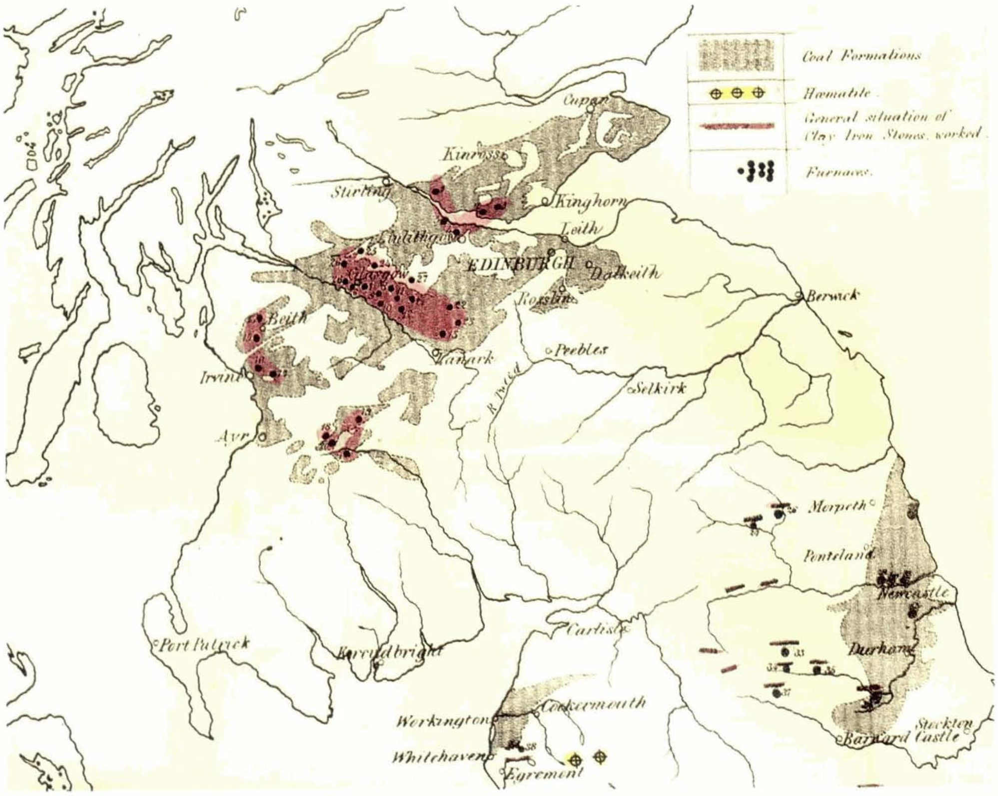


Illustration 22 Location of Scottish Iron Works, Coal and Iron Ore Deposits
Based on an 1849 map by Robert Hunt, Keeper of Mining Records at the Mining Report Office Museum of Practical Geology (Royal Commission 1849)

The main processes in the making and working of iron have been described and illustrated by W K V Gale (Gale, 1967 and 1981).

2.3 Scottish iron industries

Iron making and iron working processes required power, either to provide a mechanically assisted blast of air for a furnace or a finery, or to drive tilt hammers or rolling and slitting mills for working wrought iron. Eighteenth century ironworks were therefore constructed alongside rivers and powered by water wheels. The location of a blast furnace was at first governed also by the requirement for a plentiful supply of wood suitable for conversion to charcoal. The later nineteenth century works did not depend on water for power, or on wood for fuel, and were concentrated within the rich coal and iron ore fields of Lanarkshire, Ayrshire and Fife (Illustrations 21 and 22).

Good detailed notes and bibliographies on early iron working sites in Scotland are contained in the CANMORE database (see Section 9.2). These include Canonbie, Craleckan, Glen Kinglass, Invergarry, Letterewe (possibly established as early as 1598), Red Smiddy and Terrioch. With the iron making districts of England and Wales suffering fuel shortages, the Highlands offered waterpower sites with large tracts of woodland nearby. Most early works in Scotland were short-lived. An exception was the furnace established in the early 1750s at Bonawe by the Newland Company, of West Cumberland, later Harrison, Ainslie & Co. The works smelted iron-rich haematite ore brought from Furness and supplied iron principally to English markets, so location was determined to a large extent by access to the sea. Bonawe provided a niche market with high quality iron into the second half of the nineteenth century. The remains of the works, now in the care of Historic Scotland, include one of the best-preserved charcoal blast furnaces in Britain (Illustration 23).

In 1709 Abraham Darby had achieved a breakthrough in iron making by adapting a small charcoal blast furnace in Coalbrookdale to use coke as the fuel (Raistrick, 1953). Coke was produced by part-burning coal in open heaps to drive off sulphur and other impurities that would contaminate the iron. The first large integrated ironworks in Scotland to both make and work iron were built beside the River Carron in 1759. The founders were James Watt's patron Dr John Roebuck, with Samuel Garbett and William Cadell. The Carron Company obtained skilled workmen from the Coalbrookdale area and coke-fired blast furnaces were built not very long after the works were established. John Smeaton designed water powered

Illustration 23 Bonawe Ironworks Casting house and furnace (Picture: Historic Scotland)

blowing engines for the furnaces in the early 1760s (Skempton, 1981).

Before production at Carron began, the Carron Company acquired the established iron rolling and slitting mill at Cramond (Cadell, 1973). The Cramond works were sited alongside the tidal stretch of the River Almond in a converted grain mill. Much of the raw material for the mill, wrought 'bar iron', was imported up to the end of the eighteenth century from Russia and Sweden. The bar iron was heated in a furnace, hammered flat, then converted to strips by being passed between a pair of heavy cast iron rolls. The rolls were turned via a 16' diameter water wheel and two further water wheels drove the slitting mills. The slitting mills had rotating disc cutters placed along the rolls to divide the re-heated strip into hoop iron (for casks and wheel tyres) and rod iron (for conversion to nails and spikes).

The limitations of water power at the Cramond site was such that output did not reach the parent company's expectations of 20 tons of rod iron per week. The works manager explained heavy consumption of coal by the re-heating furnaces: 'the fall of water here is very little, by that we are probably required to heat the iron more than they do in England, as it is long in going through the Rollers and Cutters and consequently must be a great deal colder than when the wheels go with double velocity'. The working of the water wheels was also disrupted seasonally by winter spates and by summer droughts, and daily at the time of high spring tides.

Irregular water supply was a serious problem for other early industries, but the problem was particularly acute for iron making. The objective with a blast furnace was continuous operation, often for long periods, until replacement of the furnace lining became necessary. Around 1767 a Newcomen engine was installed at the Carron Works as part of a 'pumped storage' scheme, pumping water from the tailrace back to a storage pond upstream of the water wheels. The works were probably executed by James Watt in association with the Falkirk engineer Robert MacKell (Hills, 2002). Two years later, Watt took out the first of his steam engine patents, introducing the separate condenser. This is widely regarded as the single most important innovation of the Industrial Revolution. The Watt engine, once perfected, provided a long-term solution to the power problem and acted as a spur to many other iron-consuming industries. Boulton & Watt supplied steam blowing engines to several Scottish ironworks: Clyde in 1800, Calder in 1801, and Omoa and Carron in 1802 (Barker, 1992). Iron was of course used in the making of steam engines, for their boilers, and in the making of most machines that relied upon the steam engine for power.

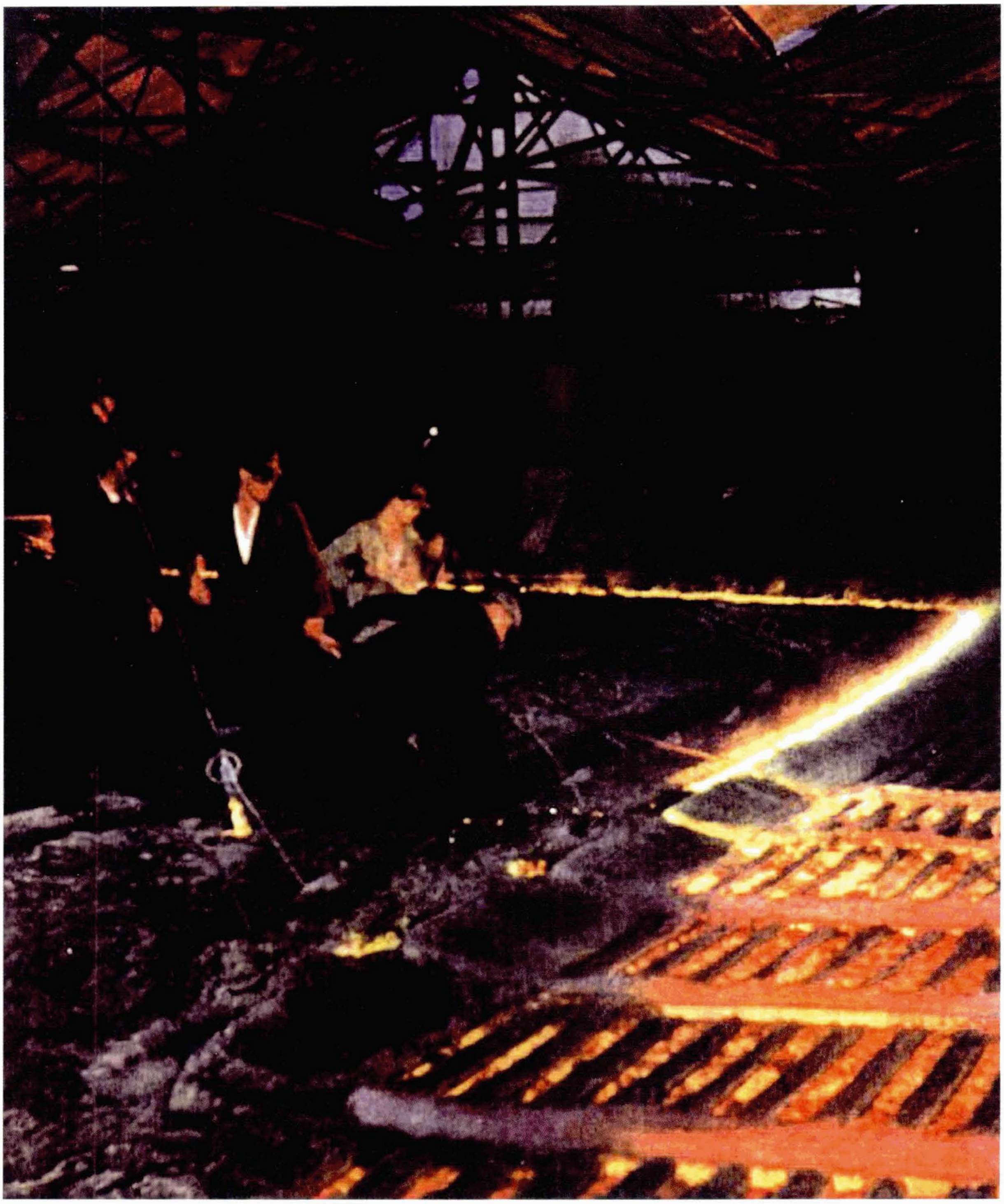


Illustration 24 Carron Ironworks. Running molten iron from the blast furnace to the pig beds (Picture: 'Carron - crucible of Scotland', Falkirk Museums, 1998)

The Carron blast furnaces were top fed with locally mined iron ore and coke from locally mined coal. Small quantities of local limestone were added too, to act as a flux. Every 6 hours or so, the furnace would be tapped at the base and the iron run into open sand beds to solidify as cast iron or 'pig' iron (Illustration 24).

In the late eighteenth century, each of four furnaces at Carron was producing 1000 tons of pig iron a year, compared with the 700 tons per year from the Bonawe charcoal blast furnace (Scrivenor, 1854). Around this time, several other ironworks were erected to exploit the rich coal, iron and limestone reserves of Scotland's 'Central Belt' - the region containing the valleys of the

Forth and the Clyde, bordered on one side by the Highlands and on the other by the Southern Uplands. By 1796 there were 17 Scottish furnaces producing in total 19,000 tons of pig iron per year. Among the larger of the early ironworks, Omoa, Devon and Wilsontown were closed in the mid-nineteenth century, while Carron, Shotts and Muirkirk were still in production over 50 years later.

Sinclair's 1792 'Statistical Account of Scotland' gives some details of the Carron Works (quoted by Day, 1876);

"...five blast-furnaces, sixteen air-furnaces, a clay mill for grinding clay and making fire-bricks for the use of the said furnaces, an engine that raises four tons and a half of water at one stroke, and on average draws seven strokes per minute. This engine goes in times of drought, and consumes sixteen tons of coal in twenty-four hours. Besides the coal consumed by the engine there are 120 tons burned every day in the works, and by the inhabitants belonging to them. Besides the air furnace there are three cupola furnaces that go by virtue of the blast-furnaces, by pipes conveyed from the machinery of the blasts; their business is much the same with the air-furnaces. There are also four boring mills for boring guns, pipes, cylinders, &c. One of the boring mills is adapted for turning the guns on the outside; they have likewise smith's forges, for making the largest anchors and anvils, as well as small work of various kinds, besides a forge for making malleable iron and a plating forge, also a forge for stamping iron, the hammer of which with the helve are both of cast metal, and weigh a ton and a half."

The making of cast iron armaments had been introduced to Scotland after the blast furnace. In 1686 the Scottish Parliament lent its support to 'the trade of Founding, lately brought into the Kingdom by John Meikle, for casting of balls, cannons, and other such useful instruments.' The making of cannon became a major part of the business at Carron, with 429 naval ships armed with 'Carronades' by 1782. The ironfounding expertise at other Scottish ironworks was similarly applied for military purposes; the Clyde Ironworks, for example, were begun in 1786 and by 1799 had 3 blast furnaces devoted mainly to making cannon and other artillery equipment. Although the arms trade was lucrative, the domestic market was not neglected (Illustration 25).

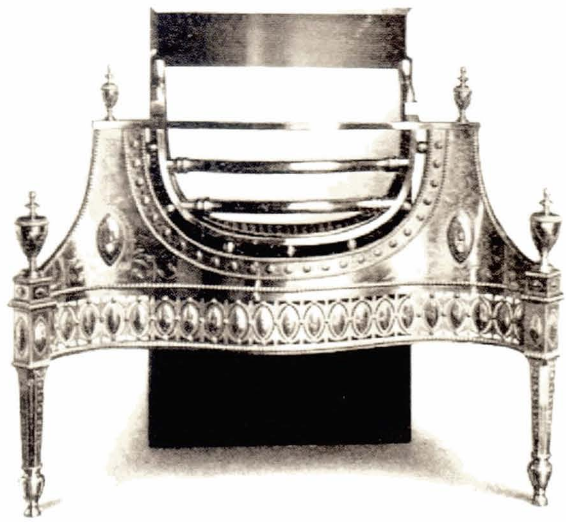


Illustration 25 A Cast iron fire grate. A reproduction of an Adam design. Artist and architect John Adam, brother of architects Robert and James Adam, was an early partner in the Carron Company (Picture: 'The Story of Carron Company, 1759-1959')

With increased pig iron production, a more efficient method for converting it to wrought iron was needed. In 1784, Henry Cort of Fontley in Hampshire patented the puddling process. The charcoal-fired finery was replaced by a coal-fired reverberatory furnace, with the fuel in a firebox and the cast iron to be converted to wrought iron in a separate hearth. Hot gases from the firebox were drawn with air across the iron by the draught from a chimney stack. The 'puddle' of molten iron was stirred with a long bar to promote the reaction of air and carbon, until the iron was decarburised. In the first part of the nineteenth century, the 'wet puddling' process was introduced, enabling rather more wrought iron to be obtained from a given quantity of pig iron.

In 1783, Cort patented the used of profiled rolls in a rolling mill. Previously, such rolls had only been used for finishing off wrought iron shaped by forging (Mott, 1978). Bars could be finished to size and other simple shapes formed between a pair of grooved rolls rotating in opposite directions, one above the other (Gale, 1965). Within the next twenty years, the 'three-high mill' was developed. A visitor to a Midlands works in 1815 described '3 grooved rollers fixed upon each other so that the bar passes backwards and forwards through the rolls with amazing velocity, and at the same heat is made into a hoop of any size in the most beautiful manner'.

As early as 1767, cast iron rails from Coalbrookdale had been laid to form a railway from the Kinnaird Colliery into the Carron Works (Raistrick, 1953). 70,000 cast iron rails were supplied in 1810-11 by the Glenbuck ironworks for William Jessop's Kilmarnock to Troon Railway, the first public railway in Scotland (Butt, 1967). However, the success of the 'Darlington Wrought Iron Railway' and the development of passenger railways created a major market for rolled

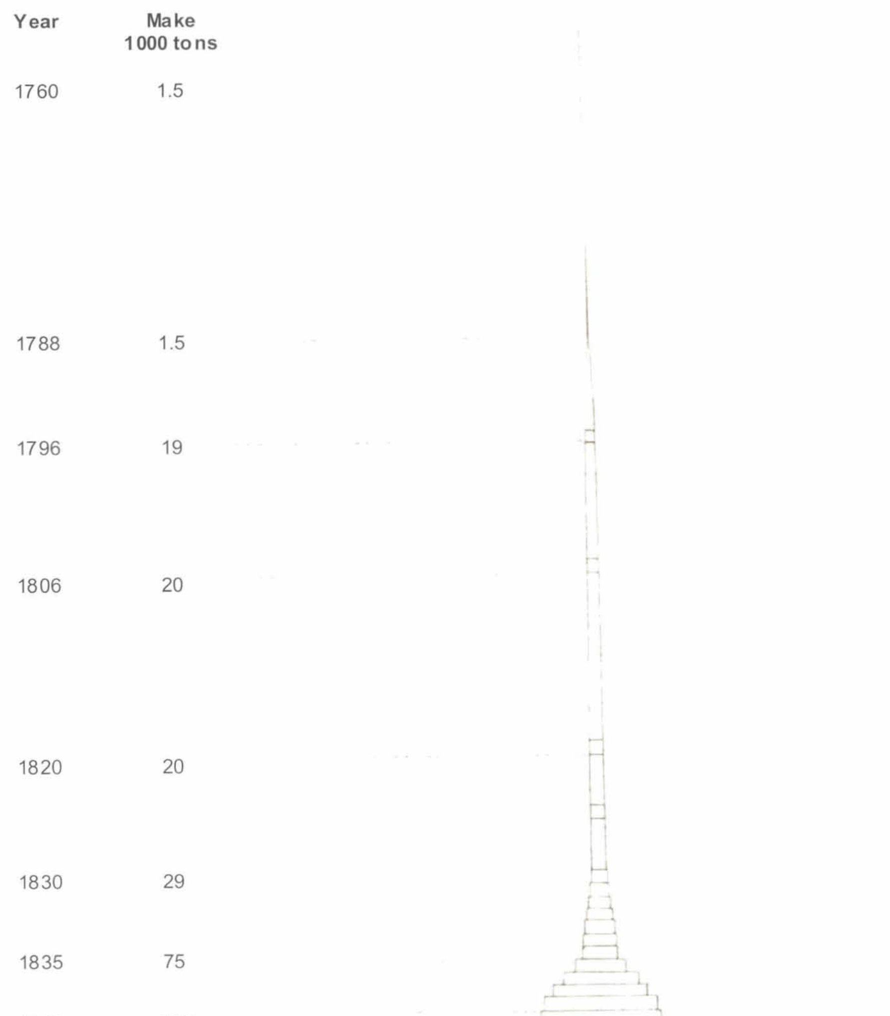


Illustration 26 *Scottish Iron Production. Based on a figure by F J Rowan of Glasgow (Rowan, 1885)*

wrought iron. With increasing demand for pig iron from foundries and for wrought iron plate from the Clyde shipbuilders, the Scottish iron industry expanded quickly in the 1830s (Illustration 26).

The rate of growth was due in part to the introduction of the 'hot blast' by James Beaumont Neilson at the Clyde ironworks. Pre-heating the blast of air to the furnaces increased productivity and enabled great savings on fuel to be made. Another factor was the 'blackband' ironstone, a rich ore containing 50-70% of iron and lying alongside the coal seams. The ore contained enough carboniferous matter to serve as fuel for calcining (part-burning) it in open heaps; a preliminary to more efficient smelting in the blast furnace. With the hot-blast it became possible to use local uncoked coal in the furnaces and this was one of the practices which led some 'Scotch iron' to develop a poor reputation in the south.

David Mushet had discovered the blackband ore at the beginning of the nineteenth century, close to the site of the Calder Ironworks then under construction near Coatbridge. This area, now known as 'The Monklands', became the focus of Scottish iron production, with the Baird's Gartsherrie Ironworks the largest works of all. Alexander Baird was established as a farmer and miller when in 1809 he leased the Woodside coalworks, near Dalserf. Afterwards, with his sons, he took on further coalfields and, in 1828, acquired a 40-year lease to work ironstone deposits near Gartsherrie. The first blast furnace was in production in 1830 and the firm became William Baird & Co. on retirement of Alexander from the business. Another son, James Baird, was responsible for innovations that involved very high blast temperatures and gave dramatic improvements in furnace productivity. In 1842 there were 16 hot-blast furnaces at Gartsherrie and in the years to 1864 other ironworks were acquired, under the Eglinton name, taking the number of furnaces to nearly 40. The total production capacity rose to 300,000 tons of pig iron per year, with up to 9,000 people employed at the various Baird works (see The Dictionary of National Biography, and Engineering, v21, 1876, p554). By the 1870s, the more accessible local reserves were being worked out and large quantities of cheaper ore from Cumberland and Cleveland were being brought in.

Although Scotland was a major producer of pig iron from the 1830s, about one third of production was exported in that form to England and another third overseas. Hot-blast Scotch iron smelted from the blackband ores was best suited to making castings rather than for conversion to high quality wrought iron. Attempts to increase wrought iron production in the mid-1840s met with only limited success, being just too late to exploit the railway construction boom. Wrought iron production did increase gradually however, so that by 1869, 338 puddling furnaces were supplying 44 rolling mills and consuming 200,000 tons of Scotch pig iron per year. Scottish foundries consumed a slightly greater quantity of pig iron in the same year (Campbell, 1980).

2.4 The early Scottish steel industry

In the early nineteenth century, small quantities of steel for cutting tools were made using either the cementation process or Huntsman's crucible process. In the mid-1840s, the Monkland Iron and Steel Company made only 100 tons of steel per year by these methods, of which 30 tons was made into files, probably a speciality of the firm. The steel produced was a tiny amount compared to the company's output of up to 400 tons of rolled wrought iron per week, which was in turn less than half of their weekly pig iron production of over 1000 tons from 9 blast-furnaces.

After the development in the mid-1850s of the Bessemer process and a decade later of the Siemens process, the bulk production of comparatively cheap steel became possible (Pole, 1888). William Dixon made trials of the Bessemer process at the Govan Iron Works but, in common with several other ironmasters, he met with little success. The chemistry of the blackband ores, in particular a high phosphorous content, made them particularly unsuitable for the early Bessemer converters and very few were built in Scotland. The first large scale open-hearth steel plant in Scotland, at the Hallside works of the Steel Company of Scotland Ltd, was designed by Siemens and in production by the early 1870s. Using haematite pig iron from Cumberland (and pig iron smelted at Shotts Ironworks from haemetite ores), the plant was soon producing 2000 tons of steel per month, mainly in the form of rails, with some steel plate and forgings. Only in the mid-1880s, when most of the 240,000 tons annual production of Scottish steel was made in Siemens open-hearth furnaces, did steel begin to be used for general structural purposes. When members of the Iron and Steel Institute visited in 1885, steel beams were being rolled at the Dalzell Works of David Colville & Sons (Iron and Steel Institute, 1885).

The shift in emphasis from iron towards steel production is reflected in company name changes (Riden, 1995). In 1888, the Glasgow Iron Company became the Glasgow Iron and Steel Company and a year later, the Summerlee Iron Company became the Summerlee and Mossend Iron and Steel Company Ltd. The Glengarnock Iron and Steel Company Ltd first operated under that name in 1891. Against this trend, the Monkland Iron and Steel Company had in the late 1880s become the Monkland Iron Company Ltd despite having opened its first open-hearth steel plant, rolling steel plate for the Clyde shipbuilders.

As steel industry technology advanced rapidly, a more innovative approach in the United States and in Germany saw Britain lose its industrial lead. As early as 1889, an engineer from Duisburg in Germany visited Scotland to demonstrate a universal steel rolling mill for parallel flanged steel girders and cruciform section columns (Sack, 1889). Such 'Universal Beams' are used today, rather than the old-style beams or joists with tapered flanges. Successful trials were made at the Motherwell works of David Colville & Sons and also at the works of the Steel Company of Scotland. However, the owners were not persuaded to invest in new plant, of a kind soon afterwards introduced on the continent. From the late 1860s, iron joists rolled in Belgian and German mills from 'soft phosphoric iron' had been imported to Britain. A high phosphorous content made the wrought iron easier to roll but rendered the end product 'cold-short'. Belgian joists, though cheap, acquired a poor reputation. In 1887, 59,206 tons of iron 'girders, beams and pillars' worth £1,000,000 were imported to Britain, the total rising to 69,313 tons the following year. Many Scottish builders would have made use of imported structural sections, except where prevented from doing so in an architect's specification.

3 STRUCTURAL USES OF IRON

3.1 Introduction

The use of iron in buildings, bridges and other structures is considered principally in this section, but reference should also be made in particular to sections 6 'Structural Elements' and 7.4 'Floor systems and their structural behaviour'. An indispensable reference in the preparation of this guide has been the Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS) publication 'Monuments of Industry' (Hay, 1986). There is no equivalent publication covering structural iron in non-industrial buildings in Scotland and this Practitioners' Guide fills some knowledge gaps in this area, while at the same time raising further questions. For information on early civil engineering works, and for the many engineers active in Scotland, the 'Biographical Dictionary of Civil Engineers' is recommended reading (Skempton, 2002). The Structures Index includes summary details of each Scottish structure featured. For researching a specific structure in detail, see Section 9 'Sources of Information and Advice'.

3.2 Buildings

3.2.1 Factories and warehouses

In Scotland, the move towards the use of iron in large, multi-storey buildings coincided with the expansion northwards of Richard Arkwright's cotton spinning enterprise. Before this, isolated examples of the use of iron in buildings might be found at ironworks or rolling mills where the material was readily to hand. As the earlier Scottish industries associated with fishing and farming developed, their buildings remained smaller in scale than the first cotton mills and continued in the tradition of masonry and timber construction. Upper floors with timber boards, joists and primary bearers were supported on solid masonry walls, with heavy timber posts to provide occasional intermediate support as needed. Strong and fire-resistant stone vaults provided storage space in the cellars and lower storeys of warehouses, bonded stores and breweries, but such accommodation was not generally suitable for factories.

Illustration 27 Bell Mill (or West Mill), Stanley Mills, Perthshire (1786-7) External view (Picture: Historic Scotland) Built to the design of Richard Arkwright, perhaps with the involvement of James Stobie, Surveyor to the Duke of Atholl, with millwright work by Lowe of Nottingham. Newly refurbished the building is of international importance as one of the finest and best preserved cotton mills with which Arkwright was concerned

Illustration 28 Bell Mill (or West Mill), Stanley Mills, Perthshire (1786-7) Cast iron storey posts with timber beams continuous over (Picture: Mark Watson, Historic Scotland)

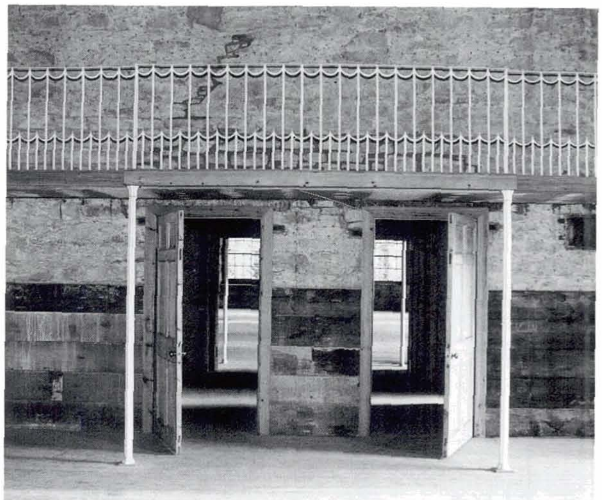


Illustration 30 New Lanark Schoolroom (1817). Fine ironwork to the gallery (Picture: T. Swailes)

Illustration 29 Green's Mill, Arbroath (1837) (Picture: Mark Watson, Historic Scotland)
A relatively unusual solid circular section cast iron column, lying on the scrap heap after demolition of the building in 1993. Columns were almost always made hollow to reduce weight, save expensive iron and because quality was very difficult to maintain in a very thick, solid casting.

Illustration 31 New Lanark Schoolroom (1817). Cast iron column with a quatrefoil cross-section (Picture: T. Swailes)

Bell Mill at Stanley in Perthshire is a fine example of the first generation of water-powered cotton mills, built in 1786 by Arkwright and his Scottish partners to house water frames (Cook, 1977). The five-storey building follows a pattern established by mills in England, with external walls of solid brickwork above a lower storey stonework plinth. To the upper floors, slender cruciform section cast iron 'storey posts' halve the spans of timber primary beams over the 24' internal width of the building (Illustrations 27 and 28). Prior to refurbishment, it was noticed that several of the cast iron posts were loose and it may be that their primary function was machinery framing rather than floor support.

For columns, cruciform sections fairly quickly gave way to circular sections. At Cartside Mill in Renfrewshire, built in 1790 but now demolished, the ends of cylindrical columns socketed into separate cast iron bases and capital. These are either of simple bell form, or extending into a plate to distribute the load over a greater area of timber. Circular cast iron columns are usually hollow, but solid columns are found occasionally, and more complex cross-sectional shapes were sometimes used for the sake of appearance (Illustrations 29, 30 and 31).

Large factory buildings with timber floors were vulnerable to fire and, in the textile industry, the dust arising from the processing of flax and cotton proved to be highly combustible. The first cotton mill at New Lanark had burned down in 1788, only two years after spinning had begun. At Stanley, a flax mill built in 1796 lasted just three years before it too was destroyed by fire. William Strutt, the son of one of Arkwright's English partners, devised a solution to the problem. In

Illustration 32 South Mills Dundee (c. date of this building 1864). Fireproof basements, partially demolished (Picture: RCAHMS)

Strutt's 'fireproof' building, the timber floor beams were protected by sheet iron, with shallow arches of hollow clay blocks forming the floors between (Fitton, 1958). Cast iron columns provided vertical support. Strutt's friend Charles Bage took this innovation a stage further at a flax mill completed in 1797 at Ditherington in Shrewsbury, by using cast iron for the beams as well as the columns (Skempton, 1962). The term 'fireproof' was a misnomer, but in Bage's building the internal structure is of incombustible materials throughout, an improvement in terms of fire-resistance. Fireproof building construction was not slow to reach Scotland. The conduits appear to have been via Manchester to Glasgow, respectively the first and second cotton spinning cities in the world, and via Leeds to Dundee and Aberdeen, which similarly disputed the title of world flax spinning capital.

In 1804-5 Henry Houldsworth built a cotton mill in Glasgow that set the pattern for other large cotton warp twisting and thread spinning mills in Scotland. Houldsworth's mill, now demolished, was powered by a steam engine supplied by the Birmingham firm of Boulton & Watt. Such firms influenced the structural design of many early factories for which they supplied engines. In some cases hollow columns served as heating pipes and in other cases as pipes to supply coal gas for lighting the mills (Stratton, 1997). An early fireproof mill, dating from 1816 but much modified since, survives in isolation on Old Rutherglen Road, Hutchesonstown, Glasgow. The building has twin rows of cast iron columns of diminishing thickness to each

Illustration 33 Crofthead Mill, Neilston: No 3 Mill built in 1881 (illustrated, to the Potts multiple arch system: compare Victoria Mill, Miles Platting) and No 4 Mill, 1885 (single arches, not shown) (Picture: T. Swailes)

Illustration 34 Banner Mill, Aberdeen Artists Perspective View. The view from plans of 1837 by W. Clerihew, shows according to the title block 'the property of Thomas Bannerman & Co. designed by Messrs. Hewes & Wren and their successors Messrs. Wren & Bennett'. (Picture: National Archives of Scotland)

brick-arched floor. Iron-framed cotton mill buildings dating from 1823-33 can be seen at Stanley and at New Lanark but many from this period have been lost.

For fireproof floors, the shallow arch remained the most popular form prior to 1880 (Illustration 32). Efforts were sometimes made in large cotton mills to reduce the construction depth and the weight of floors by introducing secondary beams between the primaries to reduce the arch spans (Illustration 33). Structural aspects of various floor systems are considered in Section 7.4.

It was common in the early Scottish mills for the structural ironwork to be supplied from Lancashire or Yorkshire as part of a package deal. The Leeds firm of Fenton, Murray & Wood supplied the structural framing, the spinning frames and a 20 horse-power steam engine for the 1808 Broadford Works in Aberdeen, the earliest surviving fireproof mill in Scotland (Watson, 1992). In 1820, the Manchester engineer and machine maker T C Hewes, who employed 140 to 150 men in erecting mills and fitting them out with machinery, supplied the framing for a fire-proof building to flax spinners Milne, Cruden & Co. of Aberdeen (Illustration 34).

At New Lanark, there are some remnants of a scarcer form of fireproof flooring system than the brick arch. Floors and a very unusual pitched roof entirely framed in iron were built in the 1820s as a lightweight construction over a waterwheel pit and to fill in between two existing gable walls (Illustrations 35 to 37). Sandstone flags supported on iron joists provided an incombustible floor. A similar form of construction is to be found in Beehive Mill, a Manchester contemporary (Swailes, 1998). An interesting variant from the same period has survived at the Grandholm Works in Aberdeen (Illustration 38).

After 1830 Dundee became the major producer of coarse linens, produced from imported flax and, later, from jute, which was also in the manufacture of floor coverings. Flax mills in particular tended to be of fireproof construction and the buildings, including the structural ironwork, were invariably designed by one of Dundee's specialist textile engineering firms (Watson, 1990) (Illustration 39).

Wool spinning did not present the same fire risk as spinning cotton or flax. In the Border wool towns and elsewhere, there are a number of large multi-storey mills with timber floors and cast iron columns. Nineteenth century warehouse buildings also tended to be timber floored (Illustration 40). Structural details progressed from simple storey posts in late eighteenth century buildings, with a variety of methods used to avoid crushing of continuous primary beams between the columns (Illustrations 42 to 44). Load transfer between storeys might be achieved by providing primary beams supported on a broad capital or on brackets either side of a continuous column, or by means of a cast iron saddle or 'crush box'.

Iron was used for greater strength in the maltings and warehouses of the licensed malt whisky distilleries erected from the 1820s onwards. The lower floors in a typical malt barn are surfaced with quarry tiles or stone slabs and split into long working aisles by rows of cast iron columns (Illustration 45). Strength was required rather than fire-resistance, and at the 1864 Rosebank Distillery in Falkirk for instance, the primary beams are of timber, flitched with wrought iron plates.

An advocate in the latter part of the nineteenth century for the use of wrought iron beams instead of cast iron beams in factories and warehouses was William Fairbairn. As a leading mill designer, he had investigated several mill collapses (Illustration 46). In 1865 an eight-storey sugar refinery building in Leith

Illustration 35 New Lanark: East End of Mill 3 (c. 1826) Cast iron supports to stone stairs and landing. Mill 3 was built fireproof to replace a timber floored mill destroyed by fire in 1819. The east end of the building formed an iron framed firebreak against Mill 4 also destroyed by fire in 1883 (Picture: T. Swailes)

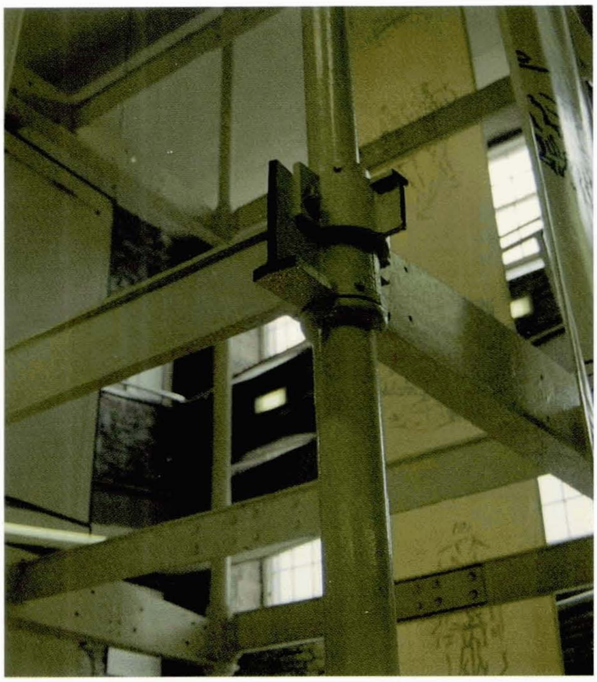


Illustration 36 New Lanark: East end of Mill 3 (c. 1826) Iron framing exposed in the access ramps area (Picture: T. Swailes)

Illustration 37 New Lanark: East end of Mill 3 (c. 1826) The iron-framed attic (Picture: T. Swailes)

Illustration 38 Grandholm Works, Aberdeen: Old Spinning Mill (1793-4, modified 1820s) Iron framing and stone flag floors (Picture: T. Swailes)

Illustration 39 Mid-Wynd Works, Dundee (1894 and 1903) The iron framing to a power loom factory under construction. The specialist textile engineering firm Robertston & Orchar of Dundee used cast iron beams here in the structural framing at a time when rolled steel beams were being used in other kinds of building. The vibrations due to power looms demanded a very solid floor and weaving sheds were usually of single storey construction with ground bearing floor slabs. In this case a constricted, steeply sloping site made 3 and 4 storey buildings with heavy suspended floors necessary (Picture: Dundee Archive and Record Centre)

Illustration 40 Robertson's (later Watson's) Bond, Seagate, Dundee (1897, rebuilt after a fire in 1907) The structure exposed by partial demolition of this former deep-plan bonded warehouse during conversion to residential use (Picture: RCAHMS/ The Drawn Evidence)

Illustration 41 Ettrick Mills, Selkirk (1835 and 1850) Front gable elevation, with date stones. Built as a mule spinning woollen mill in 1835, with timber floors on cast iron columns, extended in 1850. The fireproof floors in one of the 1850 wings are unusual in being built of local whinstone rather than brickwork (Picture: Shannon Tofts)

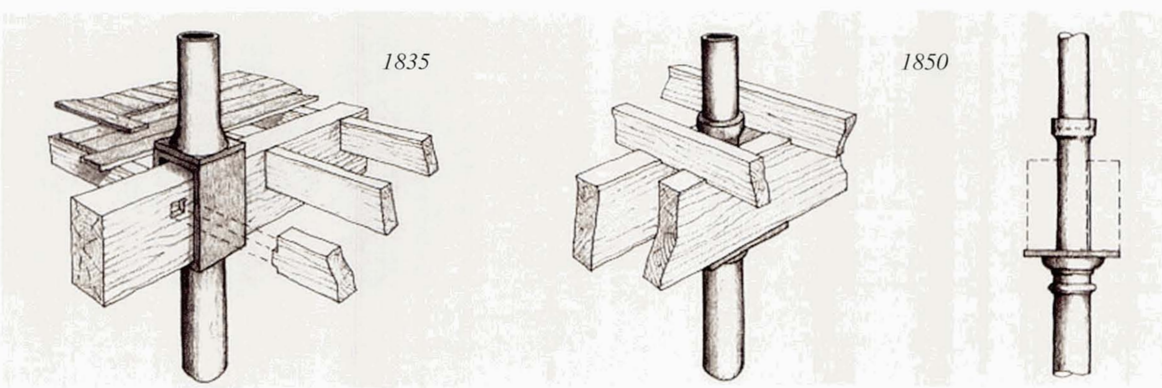


Illustration 42 Ettrick Mills, Selkirk (1835 and 1850) Cast iron column / timber floor beam details (Picture: T. Swailes)

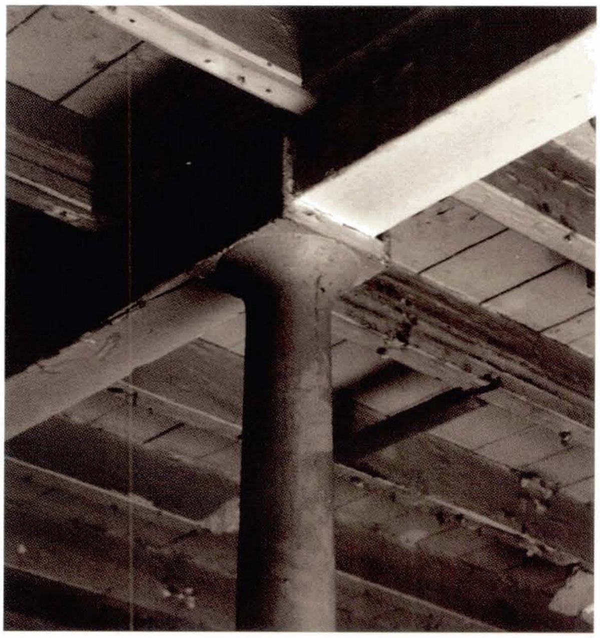


Illustration 44 Ettrick Mills, Selkirk 1835 framing (Picture: T. Swailes)

Illustration 45 Ardbeg Distillery, Islay (after 1815): malting-floor (Picture: RCAHMS, from Hay, 1986, p40) The primary beams generally are longitudinally (beneath the floor joists) so as not to reduce headroom in the direction of working (Picture: RCAHMS, from Hay, 1986, p40)

Illustration 43 Ettrick Mills, Selkirk 1835 framing, with later steelwork strengthening (Picture: T. Swailes)

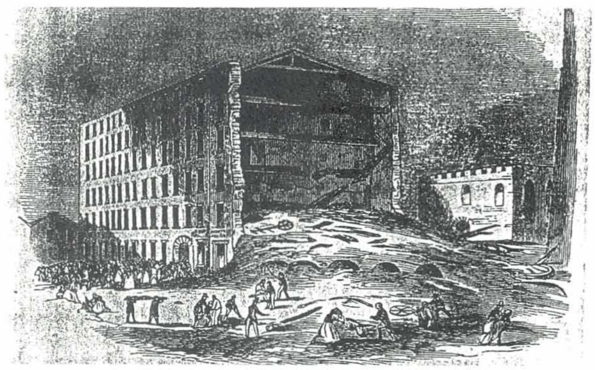
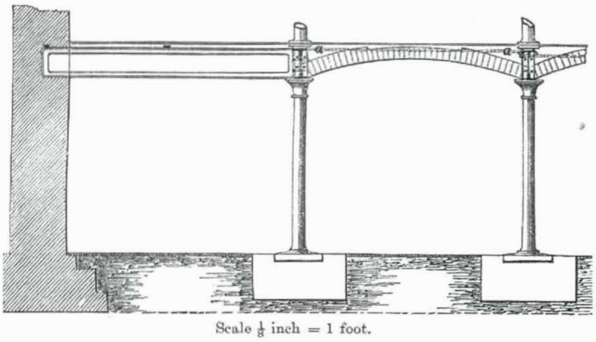


Illustration 46 The collapse of Radcliffe's Mill, Oldham, England from 'The Manchester Times', October 1844 At the time of the collapse, the construction of the building was nearing completion and a defective brick arch to the top floor was in the course of being replaced. The arch gave way, a supporting cast iron beam failed, and then other arches and beams failed in a dramatic progressive collapse that left only half of the building standing. 20 people were killed (Picture: Manchester Central Library)

collapsed during construction, killing four people. The accident was blamed at the time (perhaps wrongly) on the failure of a column foundation. A press report described the building as being 'constructed entirely of iron and brick, so as to be completely fireproof' (The Builder, v23, p159). The structural robustness of iron-framed multi-storey buildings is considered in Section 7.

As rebuilt, the Leith sugar refinery building is similar to a design first published by Fairbairn in 1864, in which riveted wrought iron is used for the floor beams instead of cast iron (Fairbairn, 1870). Some of the



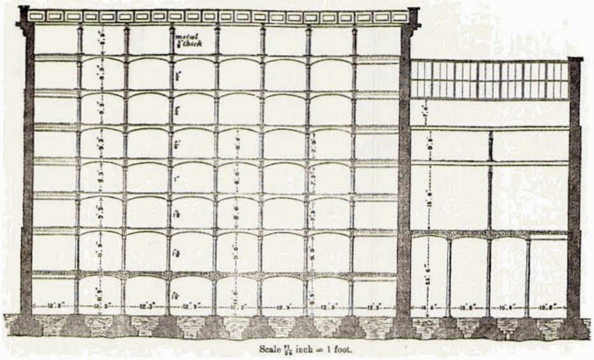


Illustration 47 Design for a sugar refinery building (c. 1864) From William Fairbairn's book, 'On the application of cast iron and wrought iron to building purposes'. The heavy floor imposed load due to 'moist sugar' was calculated at 400 lbs/ft² (19 kN/m²). The 'breaking weight' of the wrought iron girders, of approximately 29 feet clear span, was given as 106 tons, equally distributed. The wall thickness of the hollow circular columns, their external diameter permitting standardisation of beam connections, increased from 1 1/2 in. at the ground floor to 5/8 in. at the top storey. Fairbairn explained the purpose of the wrought iron ties at each level: 'These are to retain the beams straight in their places until the arches are turned from one end of the building to the other. From this it will be observed, that the tie-rods unite the arched floors and the walls on each side, forming an excellent bond, giving tenacity and unity to the structure en masse' (Source: Fairbairn, 1864)

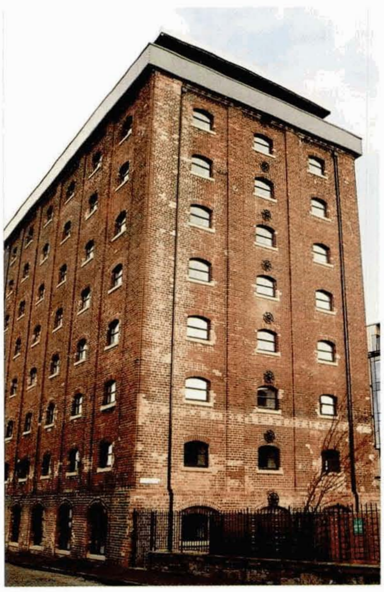


Illustration 48 Bonnington Sugar Refinery, Leith (1865-6) External view of building following conversion to residential use showing retained original cast iron pattress plates to gable and roof level water tank enclosure. For details of the collapse of the building that this replaced, refer to 'Fall of a new sugar refinery at Leith', The Builder, v23, March 4th, 1865, p159. (Picture: P. Beaton, Historic Scotland)

Illustration 49 Bonnington Sugar Refinery, Leith (1865-6) Interior view prior to conversion (Picture: T. Swailes)

upper floors are timber rather than brick, reflecting the different imposed loads associated with different stages of the refining process and perhaps a desire to minimise foundation loads (Illustrations 47 to 50).

Steel quickly eclipsed wrought iron as a material for rolled beams and joists towards the end of the nineteenth century. Steel beams were rolled by several manufacturers from the late 1870s and wrought iron beams probably not rolled after 1895 (Kennedy, 1880; Jackson, 1997). Some of the first rolled steel beams were used to support cotton mill floors in the late 1880s. Oldham in Lancashire had become the main centre for cotton spinning and the 'Oldham' model for increasingly large-scale mills spread nation-wide (Gurr & Hunt, 1989). An example is Anchor Mills in Paisley, designed by the Bradford mill architects Woodhouse and Morley (Illustration 51). In Glasgow, steel beams were used in William Leiper's Templeton Carpet Factory, completed in 1892 after the collapse of a façade during construction three years earlier. Structural design was by mill engineers G and A Harvey of Govan (Jackson, 1997).

Variants on the queen post truss, partially or wholly of cast iron, were employed to provide useable attic spaces to the earliest fire-proof mills (Illustration 52). Other solutions to the problem of providing space beneath a pitched roof included timber collar trusses, with wrought iron ties fixed to the rafter feet and at the centre of the collar beam (Illustrations 57 and 58). In the mid-nineteenth century, an attic form developed peculiar to the Dundee jute and flax mills (Illustration 55).

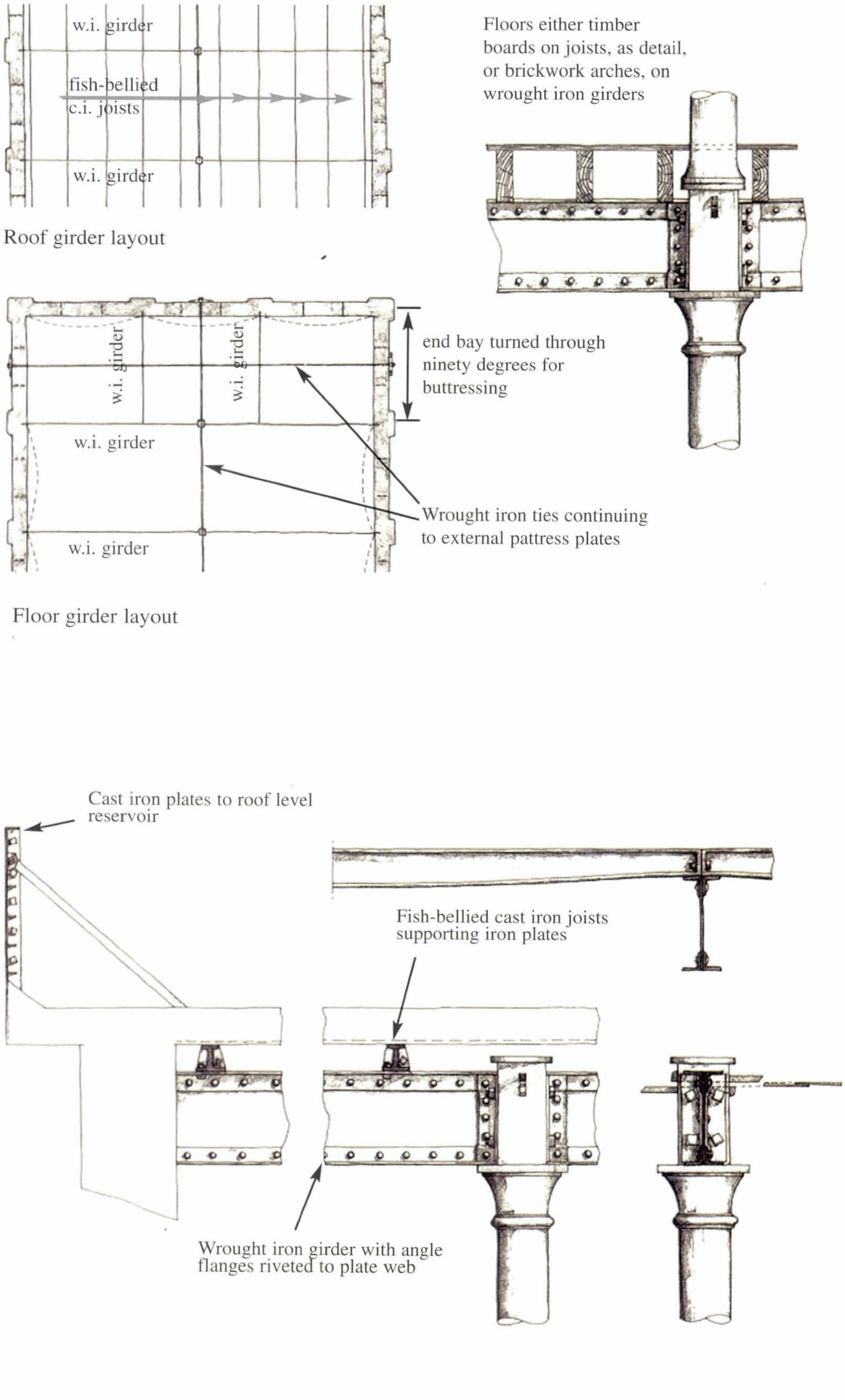


Illustration 50 Bonnington Sugar Refinery, Leith (1865-6) Structural details (Picture: T. Swailes)

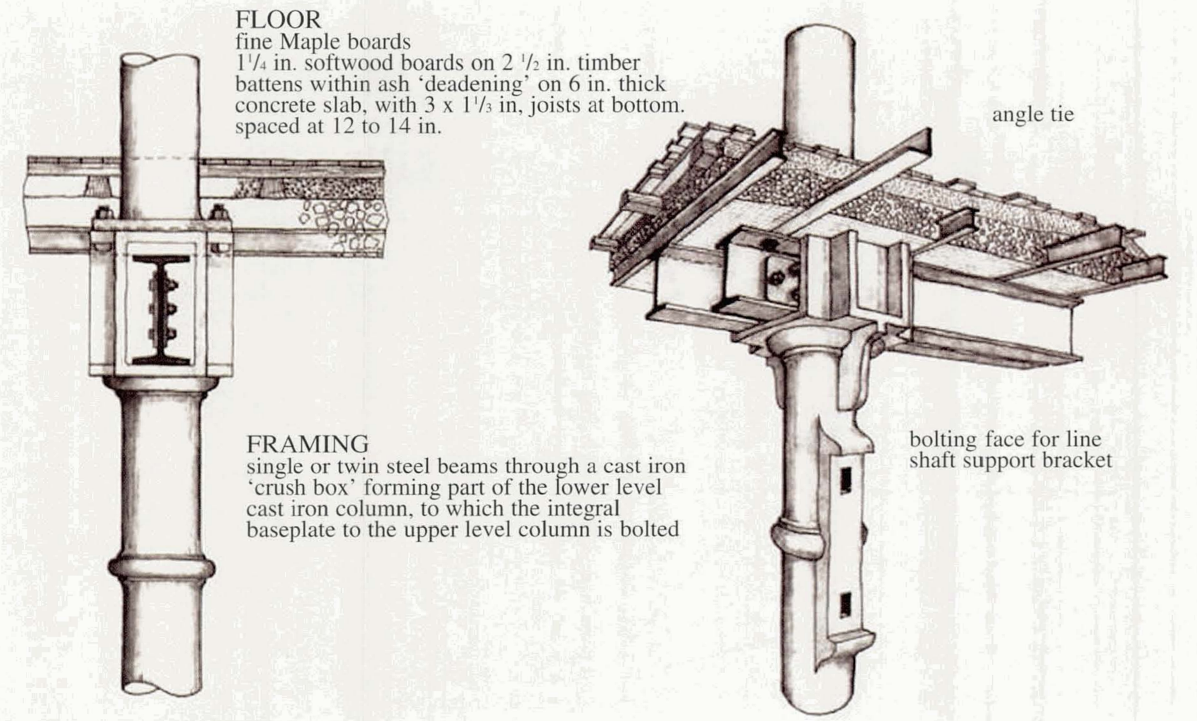


Illustration 51 Anchor Mills, Paisley: Domestic Finishing Mill (1889) Structural framing and floor construction details Large steel or wrought iron beams support flat floor slabs of closely spaced wrought iron joists in brick aggregate concrete. Cast iron columns support the beam ends. This type of 'filler joist' construction overtook the shallow arch as the favoured form of fireproof floor in mills in the 1880s (Picture: T. Swailes)

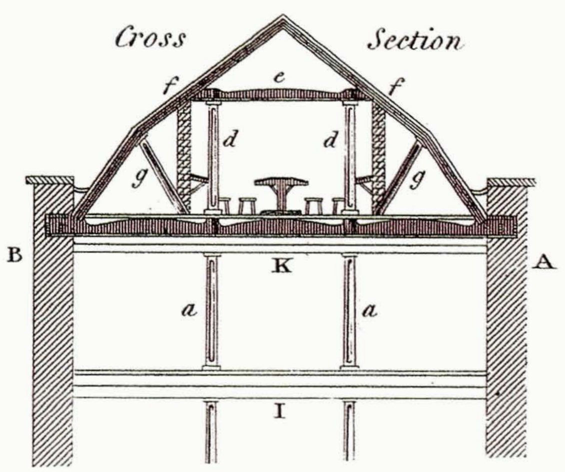


Illustration 52 North Mill, Belper: roof details (1803-4) An illustration showing William Strutt's mill with provision for a schoolroom in the roof space (Source: Rees, 1820).

Weaving was more difficult to mechanise than spinning but gradually ceased to be a cottage-based industry, as handlooms were organised within purpose built factories. Although successful power looms were developed in the 1820s, handloom weaving continued into the second half of the nineteenth century. Some later mill complexes include single storey weaving sheds that typically are tall multi-bay buildings, sometimes covering large areas, with good natural lighting via a part-glazed roof (Illustration 56). Roof structures may be of timber or of iron, spanning between cast iron columns and external solid masonry walls. Specialist ironwork contractors could supply a variety of standard roof designs (Illustrations 59 to 61).

The iron roofs to the first generation of railway train sheds provided a pattern for many later mill and warehouse roofs. Wrought iron was often used for the tension members of a truss, with cheaper cast iron or timber for the compression members. One solution was trussed rafters giving direct support to sarking boards a traditional slate roof, avoiding the need for purlins and intermediate rafters (Illustrations 62 to 64).

3.2.2 *Maritime buildings*

From the late eighteenth century, Thomas Telford and other civil engineers were responsible for the development of Scotland's inland and coastal communications, improving and building roads, canals and harbours. For much of this work, and particularly for construction in a hostile marine environment, stone masonry was the structural material of choice. However, iron structures did have advantages in that they could be prefabricated in relatively lightweight sections for ease of transportation and for rapid

Illustration 53 Cox's High Mill, Camperdown Works, Dundee (1857) (Picture: Mark Watson, Historic Scotland)

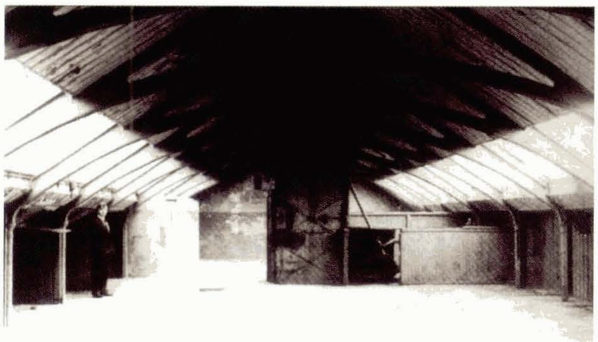


Illustration 54 Douglas Mill, Dundee (1835, rebuilt fire-proof c.1850) Similar cast iron arched trusses over an attic space survive in several Yorkshire mills (Picture: Mark Watson, Historic Scotland)

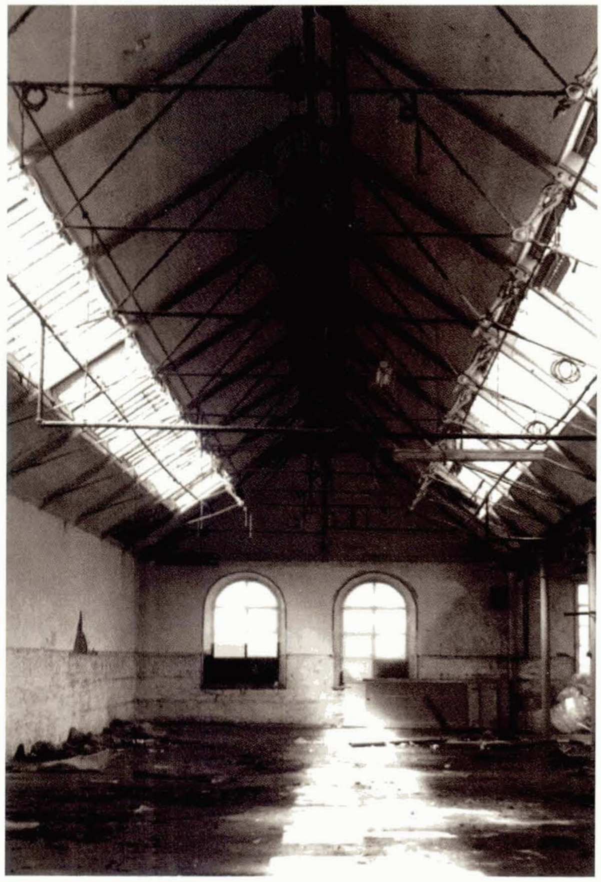


Illustration 56 Seafield Works, Dundee: West Factory (1859) Internal view of weaving shed: The Seafield Works specialised in the manufacture of jute carpet. The High Mill has been converted to housing in 1988-92 but the single storey iron framed weaving sheds were demolished. (Picture: Mark Watson, Historic Scotland)

Illustration 55 South Mills, Dundee: New Mill (1851-7, extended 1864 and 1874). A 'Gothic' cast iron framed attic This form of structure housed powered reel winding machinery. Good natural light from above was required so that the reeler could see flaws in the yarn. Large beam spans were not needed for the floors below because the spinning frames were static, though heavy, and unlike the 'mules' used for cotton and wool, did not move backwards and forwards on tracks. About a dozen attics of this type were built in the Dundee area (Picture: Mark Watson, Historic Scotland)

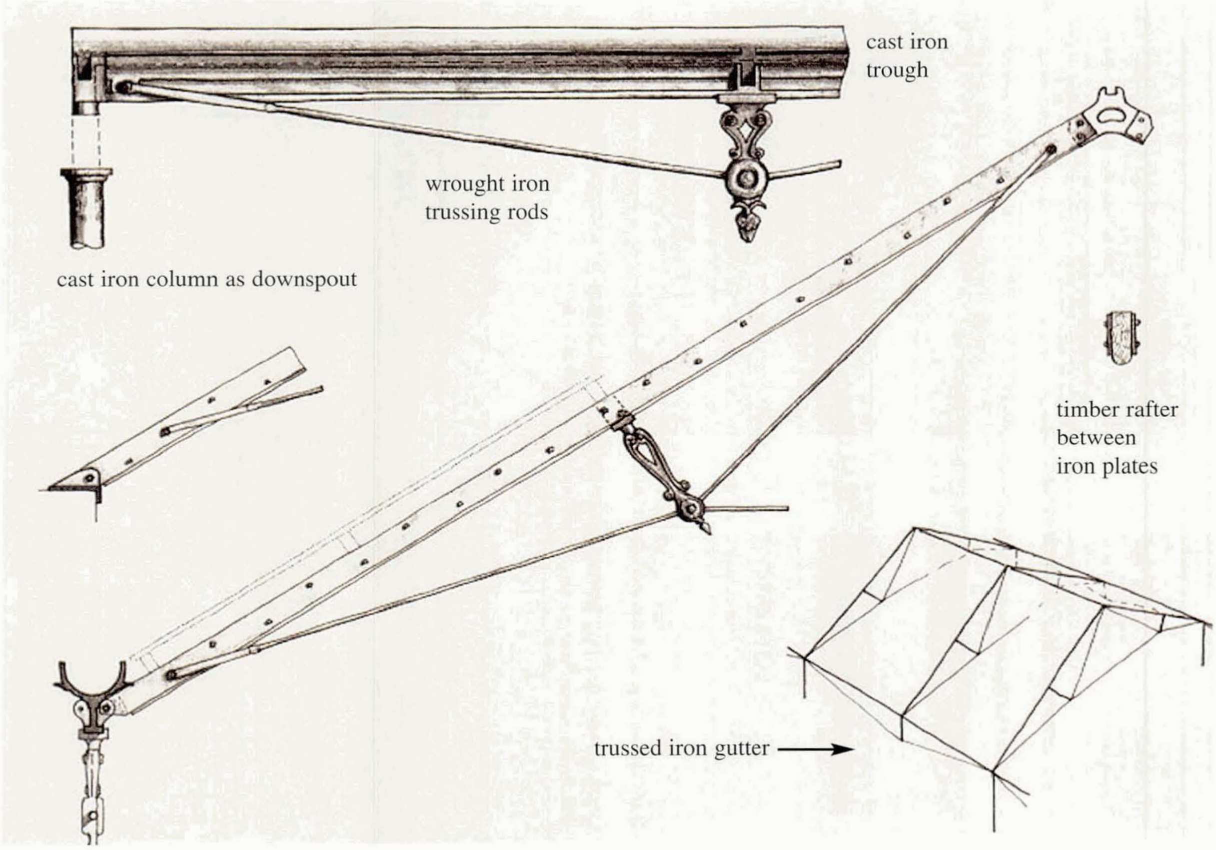


Illustration 57 Seafield Works, Dundee: West Factory (1859) Iron framing components from the weaving sheds
Structural ironwork by Robertson & Orchar, Wallace Foundry. Polonceau roof trusses with timber and wrought iron principal rafters, wrought iron tension members and decorative cast iron struts. Unusual cast iron gutter beams trussed with wrought iron rods spanned between the rainwater down-pipe columns to support alternate roof trusses.
Pieces of this weaving shed roof have been saved in the hope that a home may be found for them elsewhere (Picture: T. Swailes)

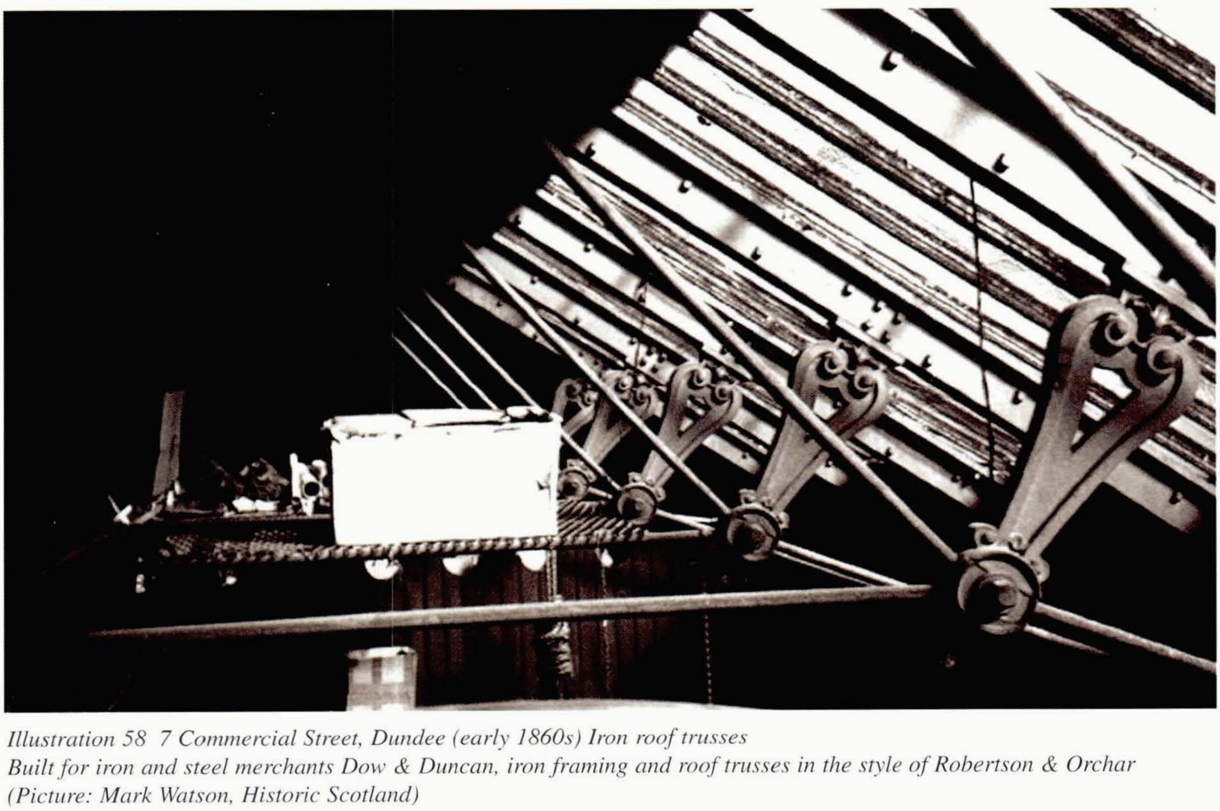


Illustration 58 7 Commercial Street, Dundee (early 1860s) Iron roof trusses
Built for iron and steel merchants Dow & Duncan, iron framing and roof trusses in the style of Robertson & Orchar (Picture: Mark Watson, Historic Scotland)

assembly at inhospitable sites (Illustration 65). In 1799, for example, Robert Stevenson had proposed a beacon-type lighthouse with cast iron pillars for the Bell Rock, as an alternative to the stone tower eventually built along the lines of John Smeaton's Eddystone lighthouse (Leslie, 1999). In 1808 Stevenson laid a cast iron railway on supports over the uneven surface of the Bell Rock. Although covered by every tide since then the railway remains in service for access to the lighthouse (Stevenson, 1824). For the sides to a lighthouse lantern, iron met the requirement for a strong and durable glazed structure, protecting the lamp but with minimal obstruction to the passage of light.

3.2.3 Train and goods sheds

Many railway buildings are essentially of traditional construction. An early example is the three-storey goods shed at the Edinburgh terminus of the Edinburgh to Dalkeith Railway (Illustrations 66 and 67). Steel beams have replaced the original timber floor beams, supported on a line of cast iron columns down the centre of the building (Illustration 68).

The roofs of train sheds provided railway engineers with the opportunity to innovate. Among the earliest to be made entirely of wrought iron was that designed in 1837 for Euston Station in London by Charles Fox, one of Robert Stephenson's assistants on the London & Birmingham Railway (Sutherland, 1964 & 1997). By 1843, Fox was senior partner with Britains pre-eminent specialist railway engineering contractor, Fox, Henderson & Co, who fabricated and erected structural ironwork for several early railways in Scotland (Illustration 69). Scotland's oldest surviving train shed, built in 1842, was removed from its original site at Edinburgh Haymarket station for preservation at the railway museum in Bo'ness (Illustrations 71 to 72).

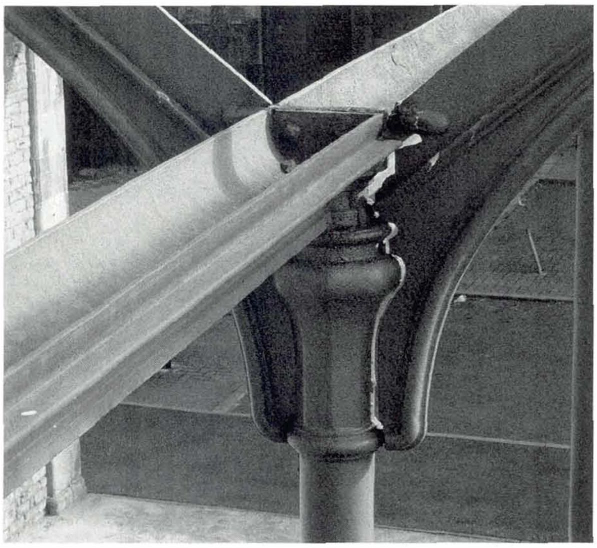


Illustration 59 Seafield Works, Dundee: Boiler House (1861) Ironwork details (Picture: T. Swailes)

Illustration 60 Seafield Works, Dundee: Boiler House (1861)
The iron skeleton of the boiler house was preserved as an interesting structural feature when the High Mill was converted to housing 1988-92. (Picture: T. Swailes)

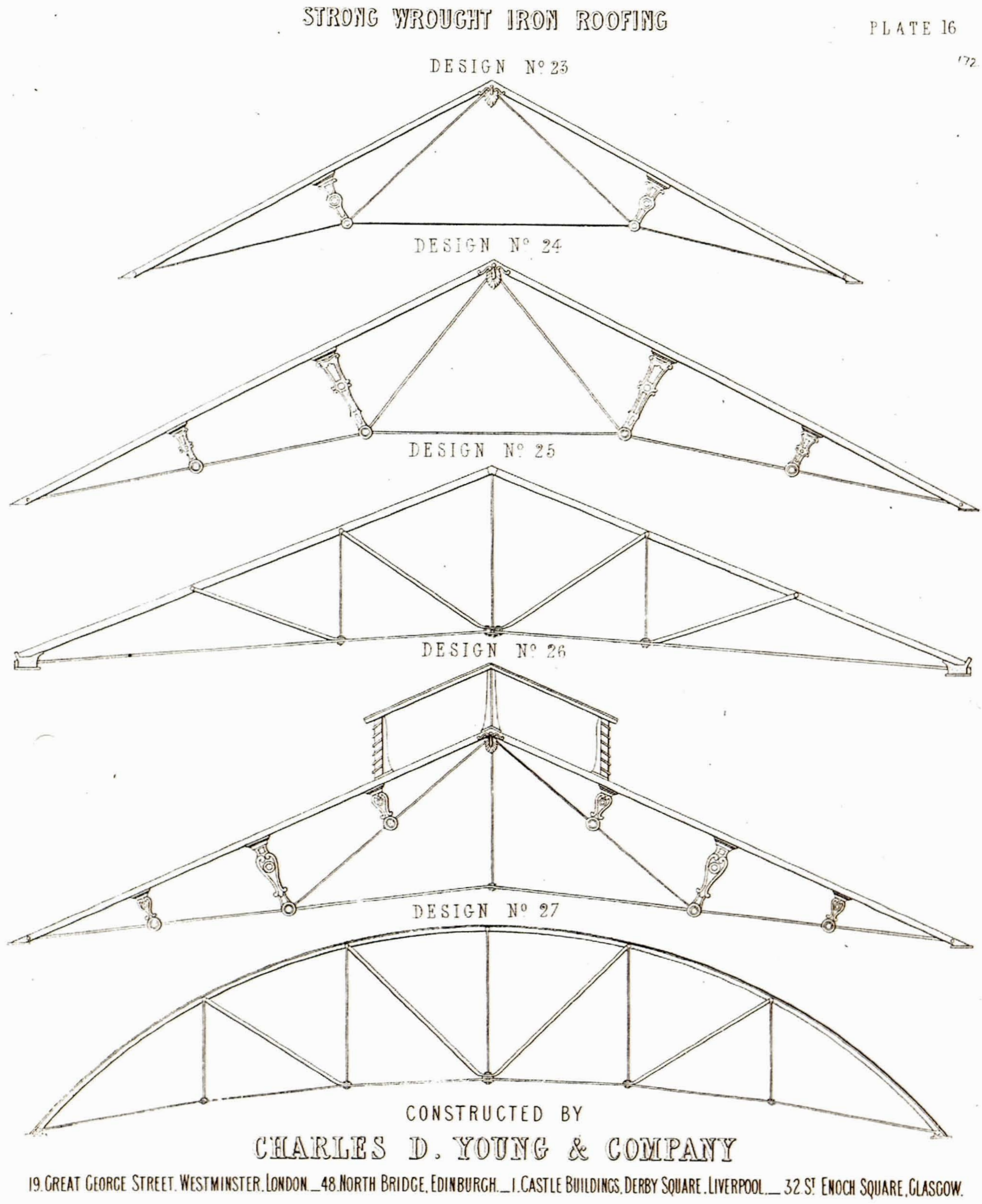


Illustration 61 Iron Roofs (1860s) Standard truss details from a manufacturer's promotional brochure. From the catalogue of Charles D. Young & Company, Engineers, Ironfounders, Contractors, &c., of the Britannia and St. Leonard's Ironworks, Edinburgh, 'Illustrations of iron structures for home and abroad. Consisting of stores, dwelling-houses, markets, arcades, railway stations and roofings, &c., &c., constructed of wrought and cast iron and corrugated sheets' (Picture: The Library of the Institution of Civil Engineers)

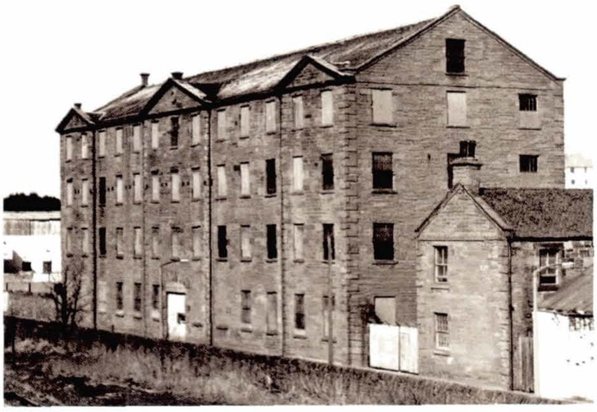


Illustration 62 Baltic Works, Arbroath (1861) External view (Picture: T. Swailes)

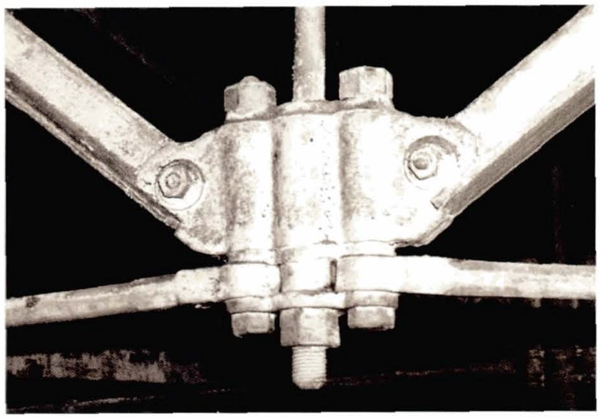


Illustration 63 Baltic Works, Arbroath (1861) Tie bar mid-span connection (Picture: T. Swailes)

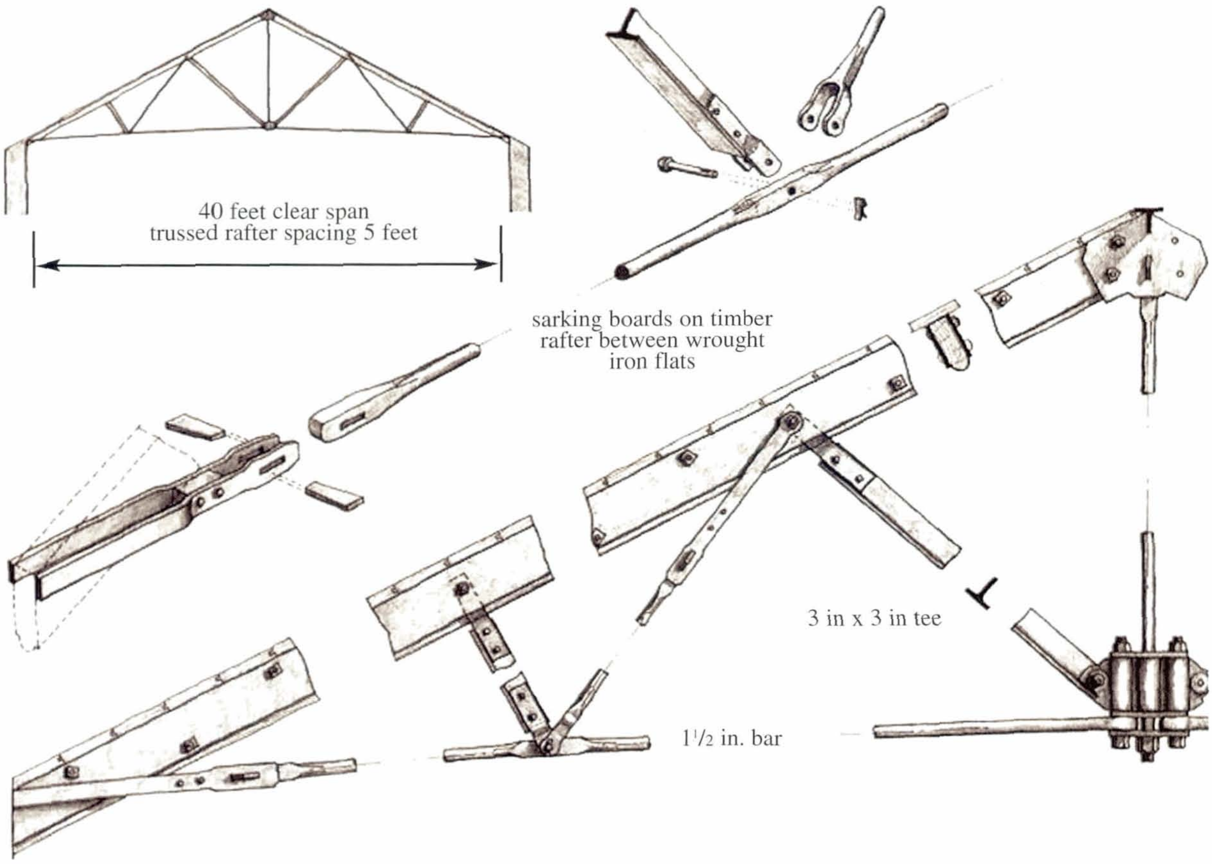


Illustration 64 Baltic Works, Arbroath (1861) Wrought iron roof details (Picture: T. Swailes)

Very long, single bay buildings, similar in form to the early train sheds, were built in ports for the temporary dry storage of goods on the quayside, between ship and train or wagon. The Dublin based engineer and ironwork contractor Richard Turner used 'deck beams' as curved principal rafters in his roofs (Illustration 73). Deck beams were so called as they were developed originally for use in the construction of ships such as the SV Carrick, now at the Scottish Maritime Museum in Irvine.

Corrugated iron, patented in 1829 by H.R. Palmer, a London civil engineer, provided a covering material with a strength and lightness to match the supporting iron structure below. Portable iron buildings of corrugated iron for the export market were introduced in the 1830s (Bellhouse, 1991). The first iron framed ship building slip roofs, constructed in Pembroke Dockyard in 1844-5, were covered with corrugated iron, to the following specification: 'No. 17, Birmingham wire gauge, weighing about 2½ lbs. to the

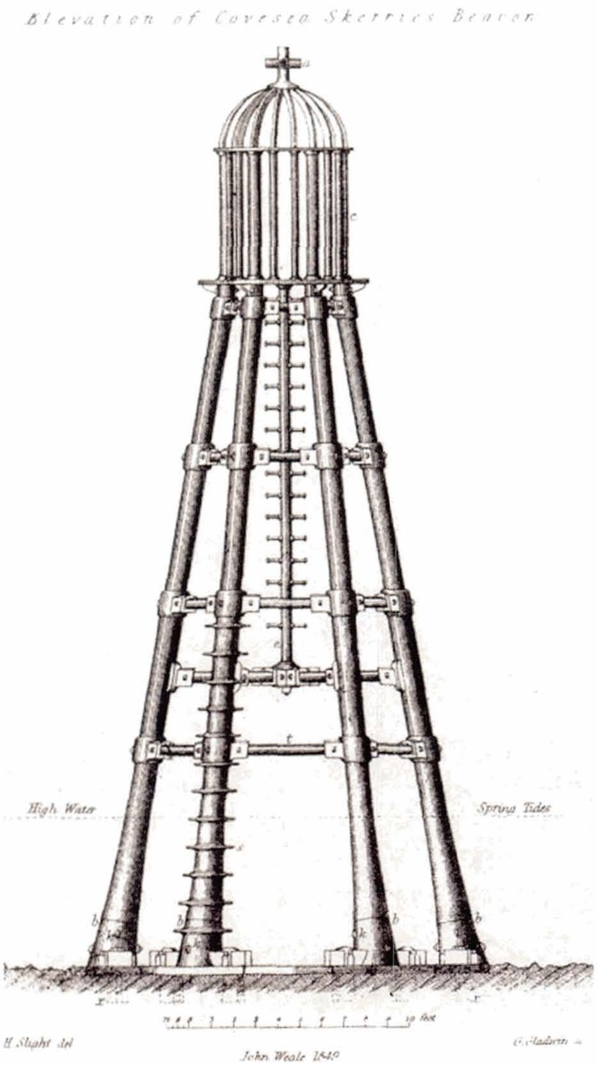


Illustration 65 Iron Beacon on Halliman Scars, near Covesea Skerries (1844) Illustrated in Alan Stevenson's Lighthouse Treatise (Picture: R. A. Paxton)

Illustration 66 The Edinburgh and Dalkeith ('Innocent') Railway Goods Shed and Terminus (c.1840) External view (Picture: RCAHMS)

Illustration 67 The Edinburgh and Dalkeith ('Innocent') Railway Goods Shed and Terminus (c.1840). Internal view at 'rail level' prior to refurbishment. The present floor level is marked on one of the bases. (Picture: Crown Copyright: RCAHMS. Reproduced courtesy of JR Hume)

Illustration 68 The 'Edinburgh and Dalkeith ('Innocent') Railway Goods Shed and Terminals (c.1840)
Steel beams on cast iron columns, over the cafe at first floor level. The steel beams replace early timber beams and bear the rolling mark
LANARKSHIRE STEEL CO LD SCOTLAND 12 x 6
(Picture: T. Swailes)

foot; the sheets are 2' - $2\frac{3}{4}$" wide, containing six corrugations: their usual length is 7' , but they are cut to suit what may be required; they are laid with a top lap of $4\frac{1}{2}$", riveted with two rows, $2\frac{1}{2}$" apart, of $\frac{1}{2}$" x $\frac{3}{16}$" rivets, $4\frac{1}{4}$" from each other, and with a side lap of $1\frac{1}{4}$", fastened by one row of rivets $8\frac{1}{2}$" asunder' (Williams, 1847). The earlier timber-framed ship building slip roofs had been covered with plain sheet iron, sheet copper, zinc, slates, tarred paper, or canvas.

Turner's prototype for the trussed arched form of roof was his 153' 6" clear span roof to Lime Street Station in Liverpool, constructed in the late 1840s (Turner, 1850). This was soon surpassed by Fox, Henderson & Co.'s roof of 211' span for Birmingham New Street Station, designed by E.A. Cowper (Phillips, 1855; Cowper, 1854). The Edinburgh engineer and pioneer

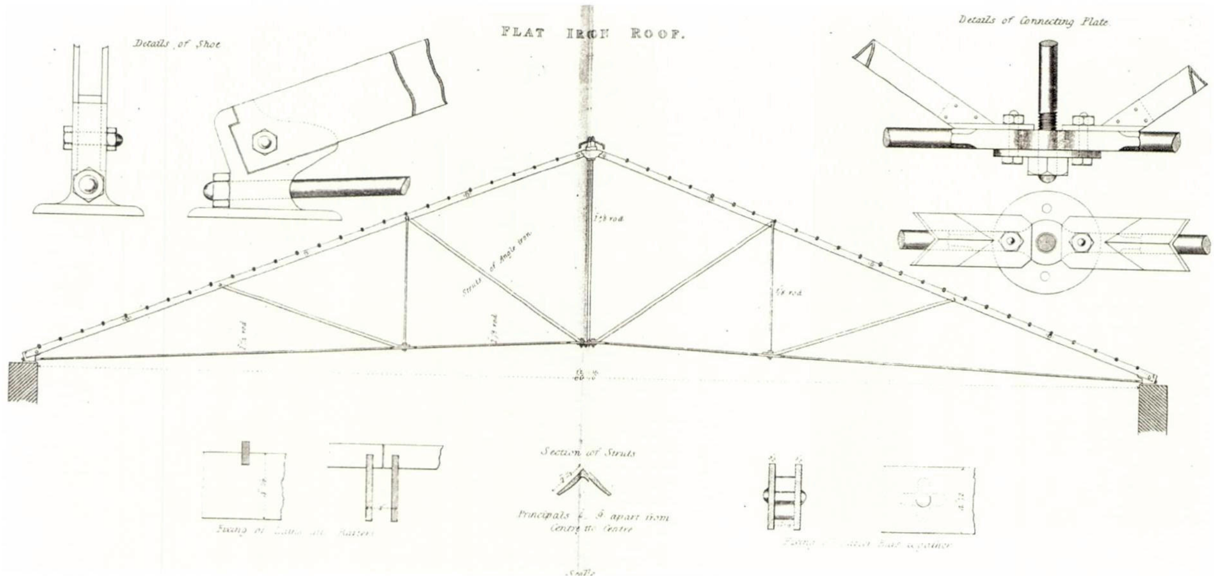


Illustration 69 A wrought iron roof by Fox, Henderson & Co. (early 1840s) Roof span 60', trusses spaced at 4' 9" centres, principal rafters of timber sandwiched between 4½" x ⅜" wrought iron plates, and laths of wrought iron bar. A similar form of principal rafter was used in the first roof at Cowlairs Station, Glasgow, on the Edinburgh to Glasgow Railway. (Denison, 1843)

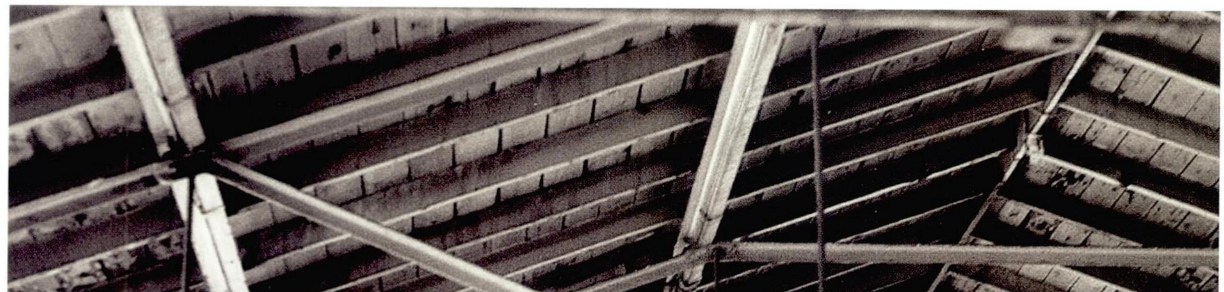


Illustration 70 Great Eastern Hotel, Glasgow, formerly R. F. and J. Alexander's Cotton Spinning Mill (1848). General view of lightweight wrought iron roof. Mast roofs of this kind were to railway station trains and goods sheds and have been replaced. An example survives at Glasgow's Queen Street Station alongside the later tied arch tram shed (Picture: T. Swailes)

Illustration 71 Haymarket Station Edinburgh (1840). A broken cast iron strut from a roof truss in storage at the Bo'ness Heritage Area where most of the trainshed is now re-erected. The cover plate has been removed, showing anchorage slots for 'upset' iron tie bar ends. (Picture: T. Swailes)

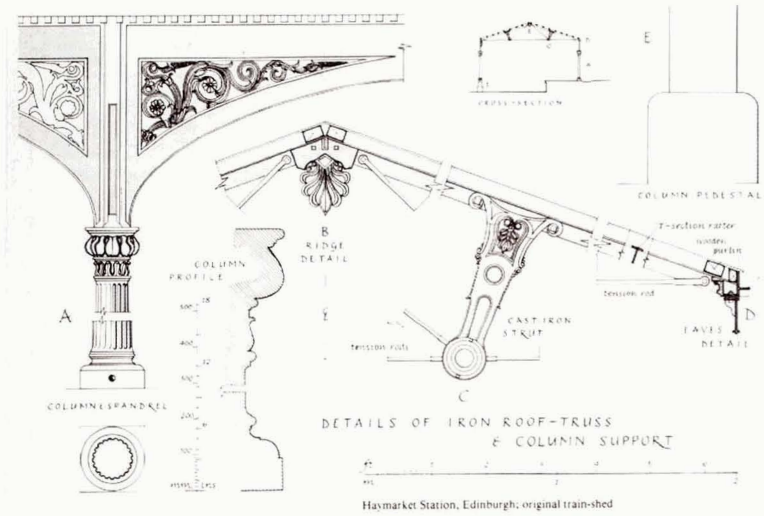


Illustration 72 Haymarket Station Edinburgh (1840), Trainshed roof ironwork details (Source: Hay, 1986/ RCAHMS)

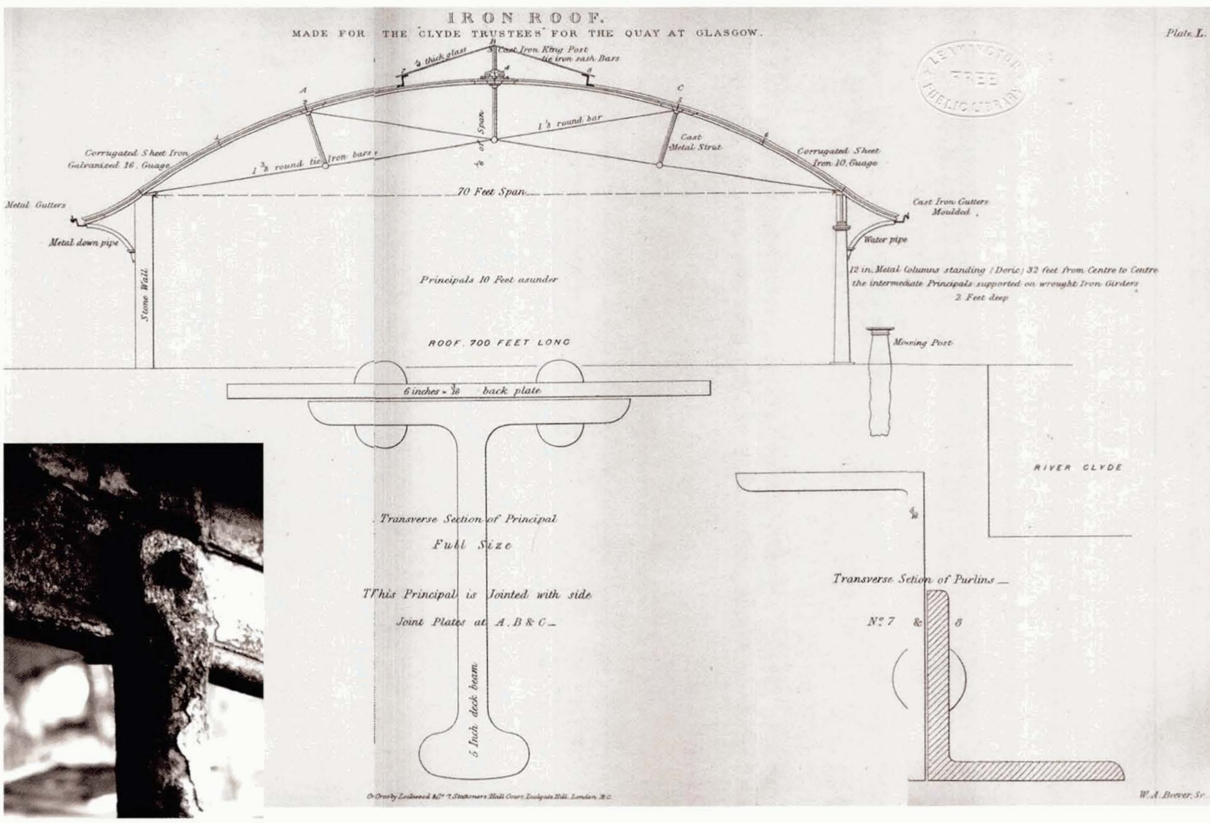


Illustration 73 Glasgow transit shed, by Richard Turner. The 700 feet long 'transit shed' once stood alongside the Clyde. Deck beams 5" deep formed the curved principal rafters to wrought iron trusses spaced 10' apart and supporting tee section wrought iron purlins. The river side of the roof was covered with 'corrugated sheet iron 10 gauge' and to the land side, where presumably appearance was more important, 'corrugated sheet iron, galvanised 16 gauge' (Source: Tarn, 1886) Inset SV Carrick (1864, Scottish Maritime Museum, Irvine. Deck beam and supporting iron post. The original rolled wrought iron deck beam is to the left of the post. To the right of the post is a replacement, made from a wrought iron bar with a plate welded to it. (Picture: T. Swailes)

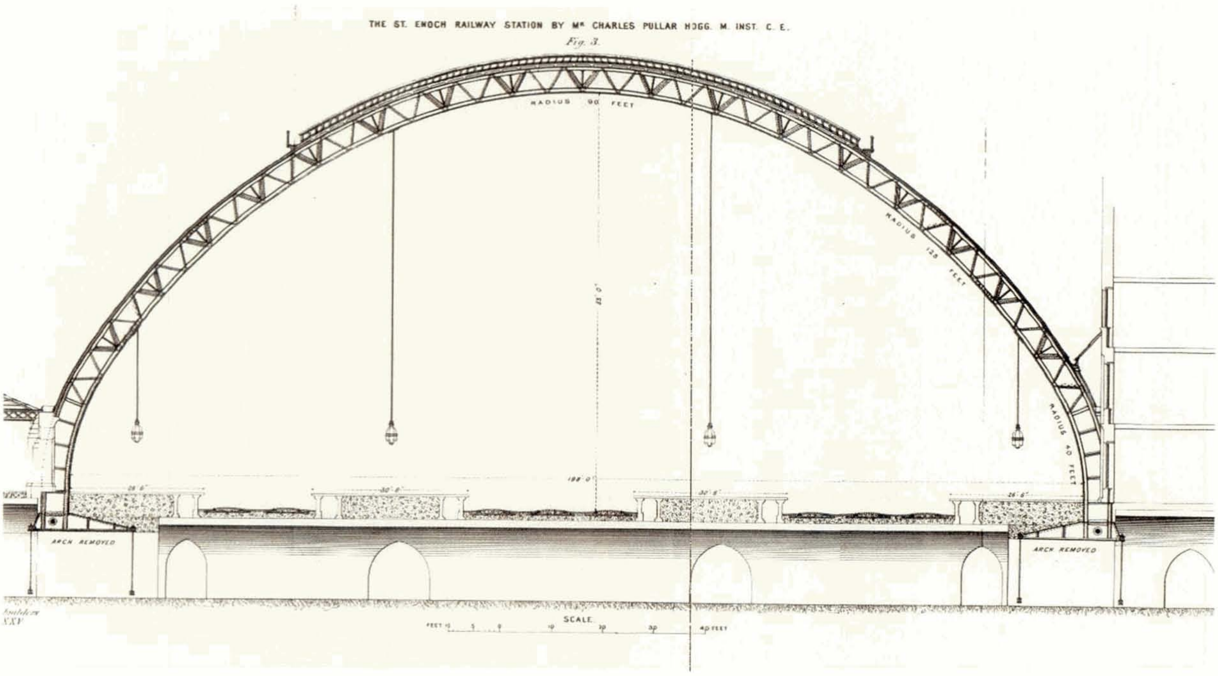


Illustration 74 St Enoch Railway Station Roof, Glasgow (1877, now demolished) (Source: Hogg, 1882)

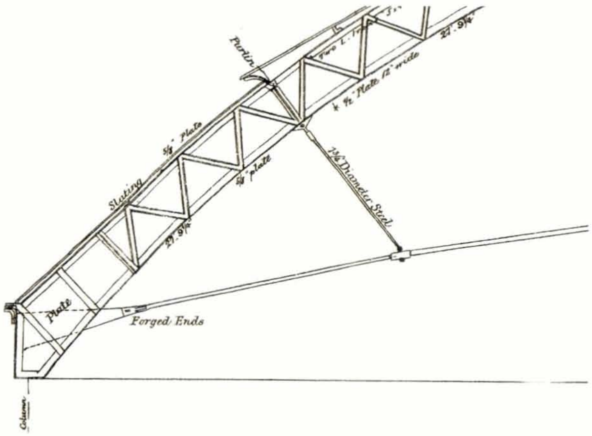


Illustration 75 Queen Street Station, Glasgow: Main train shed roof (1880) Wrought iron trussed arch ribs and steel tie with forged ends (Source: Walmisley, 1888).
Possibly the first engineer to specify steel ties in a roof of this kind was John Fowler at Liverpool Terminal Station (1872-3), for which tests on the steel gave a yield stress of 22 tons/ in² (340 N/mm²). The reduction of the test specimen cross-sectional area at the point of fracture, a measure of ductility, was 15% (Matheson, 1873)

Illustration 76 Queen Street Station roof maker's plate (Picture: Network Rail)

of 'graphic statics' R H Bow was involved in structural analysis aspects of the Birmingham roof (Bow, 1873). The void left by the bankruptcy of Fox, Henderson & Co. in 1857 was filled by a number of firms, including the Derby firm of Andrew Handyside & Co. Handyside's completed Scotland's largest roof span in 1877, the 204' span train shed to the now demolished St. Enoch Railway Station in Glasgow (Illustration 74). A roof modelled on the St Enoch roof survives over what is now the Greater Manchester Exhibition Centre.

In common with suspension bridge chain-bars, the critical tension members in larger trussed arch or tied arch roofs were of superior material. Proof-testing would be to a stress well in excess of the working stress taken for wrought iron joists and boiler-plate girders. Bessemer's patent of October 1855 had anticipated this application for steel for the making of tension bars rolled in one piece (see Civil Engineer & Architects Journal, v19, 1856, p242). However, early Bessemer steel proved unsuitable for such applications

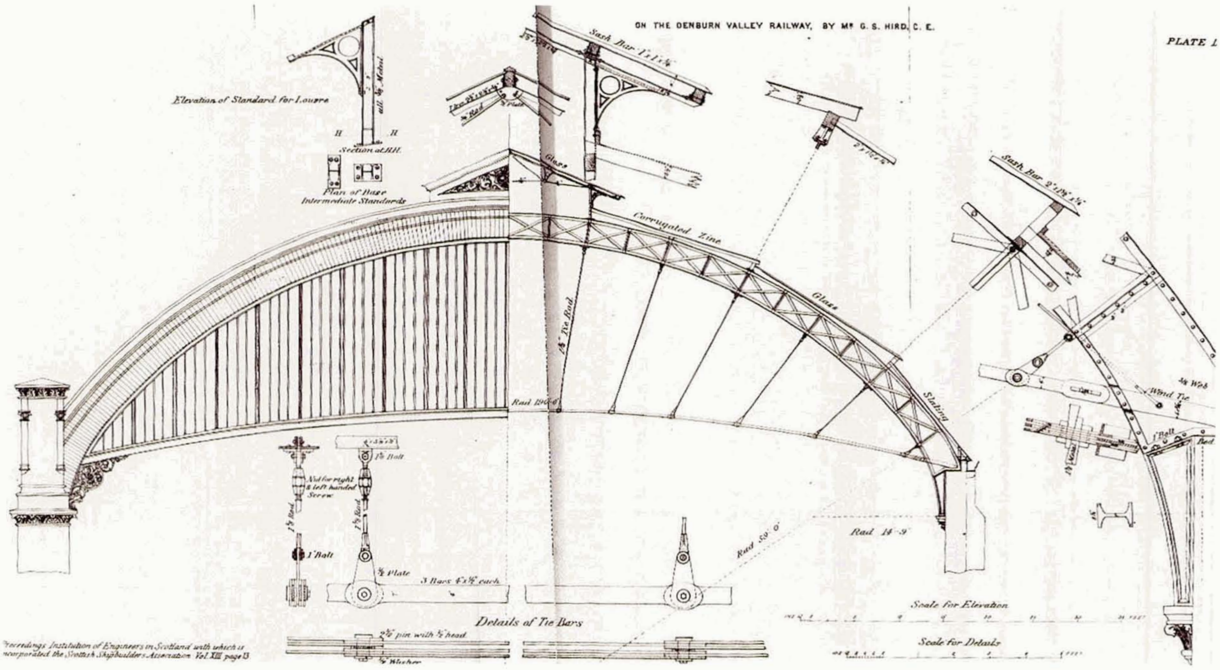


Illustration 77 Aberdeen Station structural ironwork details to the old roof (1866-70) 'Howard and Ravenhill's patent bars' were used for the critical tie members, with the bars and their eyes rolled as one piece, rather than as separate pieces forge welded together. The roof was constructed by the Aberdeen firm of James Abernethy & Co. (Hird 1869)

Illustration 78 Queen Street Station, Glasgow: Main train shed roof (1880) Tied wrought iron arches on cast iron columns. Designed by the civil engineer James Carswell, with steel tie bars to the principal wrought iron roof arches. (Picture: T. Swailes)

Illustration 79 Queen Street Station, Glasgow: Main train shed roof (1880). The gable screen and the cross-braced roof (Picture: T. Swailes)

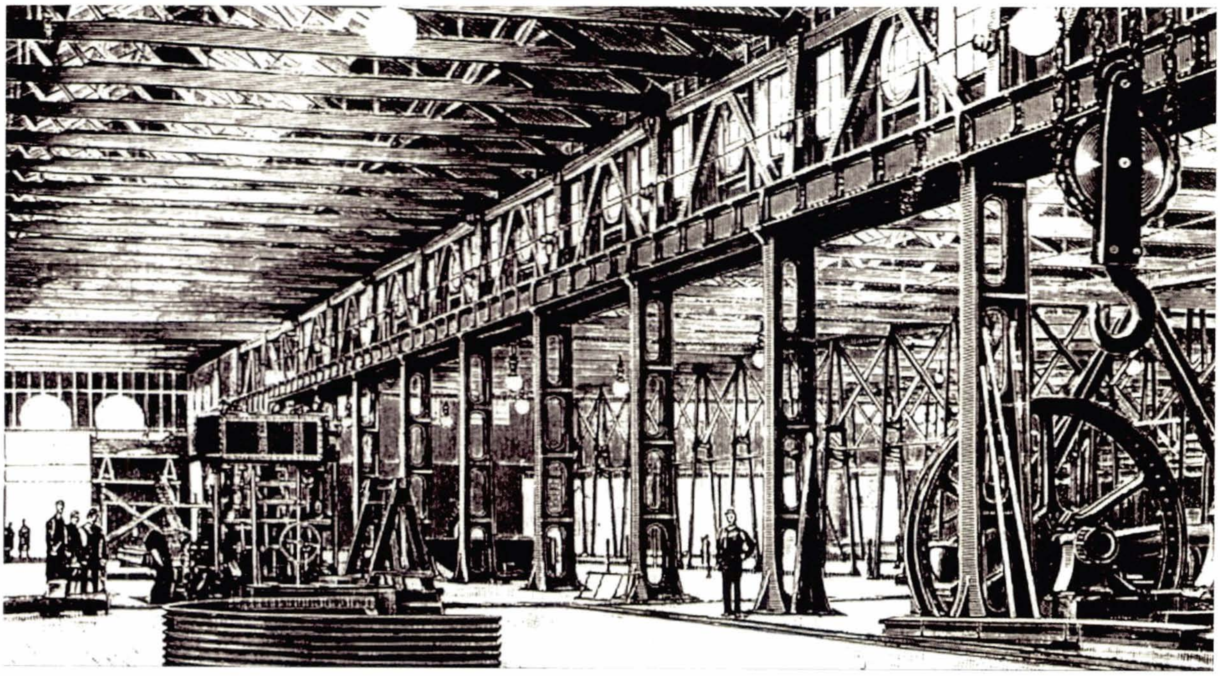


Illustration 80 Glasgow Exhibition Building, The Machinery Hall, 1888 (Source: Engineering, 1888)

(Illustration 75). Howard & Ravenhill's patent tie bars were specified for the original roof to Aberdeen Station, now replaced (Howard 1849; Hird 1869) (Illustration 77). A feature of many of the large 'engineered' iron roofs is tension cross-bracing between the principal rafters and beneath the roof covering. This is apparent at Glasgow's Queen Street Station, which has a fine over-arching roof (Gomme & Walker, 1968) (Illustrations 76, 78 and 79).

3.2.4 Heavy engineering workshops

In the late nineteenth century, massive single-storey machine halls or erecting shops were distinctive landmarks along the Clyde Valley. Several examples from 1890 or later are illustrated in 'Workshop of the British Empire' (Moss, 1977). Shipbuilding was principally an outdoor activity but heavy engineering work on marine engines or railway locomotives, for example, was carried out under cover. Gantry cranes handled heavy components over large clear floor areas. In most of these buildings heavy section timbers were used extensively, both in the roofs and for stability bracing above crane girder level. Typically, the crane rails were laid on wrought iron plate girders, supported in turn on heavy cast iron stanchions of I-section and with stiffened perforated webs (Donnachie, 1977) (Illustration 80). From the mid-1840s, iron buildings were erected over ship slips in the Royal Dockyards to enable wooden ships to be built under cover, but it appears that the spread to Scotland of this practice and the buildings associated with it was rather limited (Sutherland, 1989). Where Scotland did perhaps take a lead was in the early use of steel for industrial buildings as, after the success of the Forth Bridge, Arrol's constructed 42 steel-framed workshops of various types in the last few years of the nineteenth century (Jackson, 1998).

3.2.5 Public, commercial and residential buildings

It is fairly easy to understand the structural arrangement of an industrial building in which the framing is clearly visible. In other large buildings, until the early twentieth century the exclusive design province of architects, the framing of floors and roofs is very often concealed. Sometimes elaborate measures were taken to disguise structural ironwork; making assumptions is unwise, and surprises are to be expected (Illustrations 81 to 85). Cast iron was used quite extensively in the 19th Century terraces of Glasgow's West End, although it may sometimes be mistaken for stone (Illustration 83).

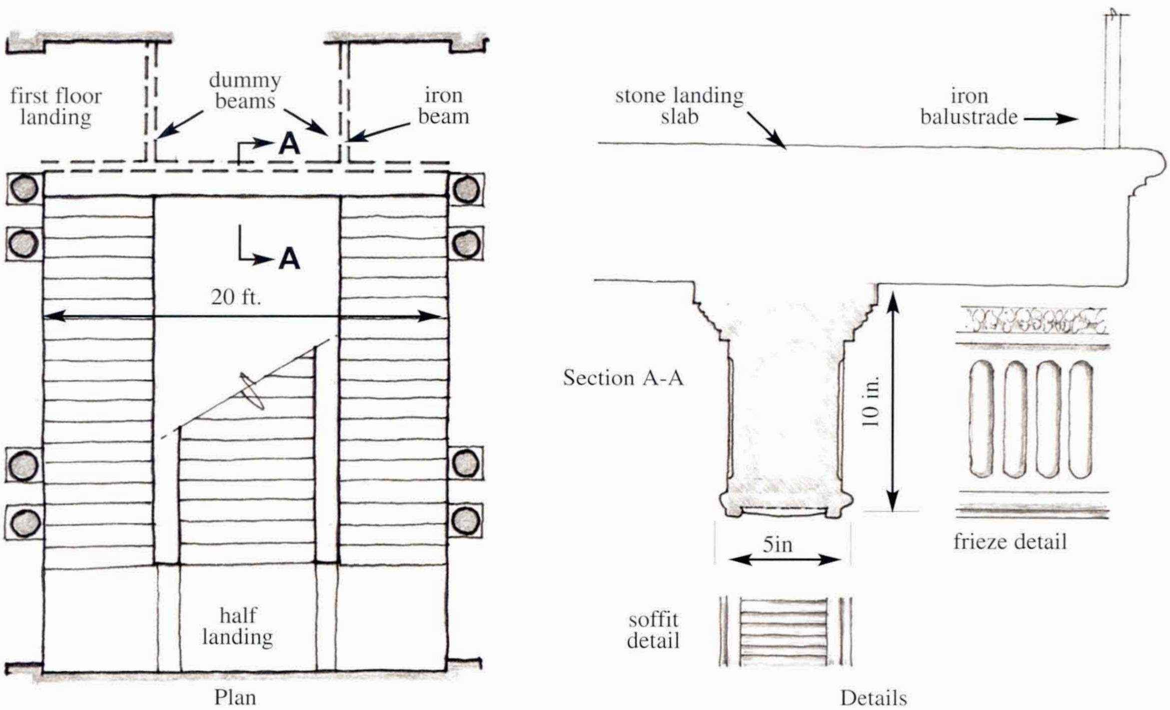


Illustration 81   Heaton Hall, Lancashire (1776) Staircase landing support beam Plan and details (Drawing: T. Swailes)

Illustration 82   Heaton Hall, Lancashire (1776)
Staircase landing support beam Examined initially from ground floor level, the slender beam was assumed to be timber with an iron flitch plate. On investigation with a 'cover meter', the beam was found to be (most probably) of solid cast iron, moulded to exactly match the decorative plasterwork. Secondary beams of identical appearance provided a second surprise, being hollow 'dummies', provided purely for aesthetic reasons.
(Picture: Joe Marsh, UMIST)

Illustration 83 Royal Crescent, Glasgow (c.1839)
Cast iron column supports to a ground floor bay. The steps over the basement well are supported on cranked cast iron beams. Large cast iron columns flank porticos to other properties in Royal Crescent (Picture: T. Swailes)

Illustration 84 Balintore House, Kirriemuir, Angus (1859) Cast iron primary girders and timber secondary floor beams exposed in the semi-derelict building (Picture: Paul Mitchell, Angus Council)

Suitable member sizes and layouts for timber framed floors to large rooms were published in contemporary carpentry manuals (Illustration 86). A timber girder for a long span would generally be made by first squaring off a tree trunk, sawing it down the middle, then bolting it together with the sawn sides outwards. This gave an opportunity to examine the centre of the tree

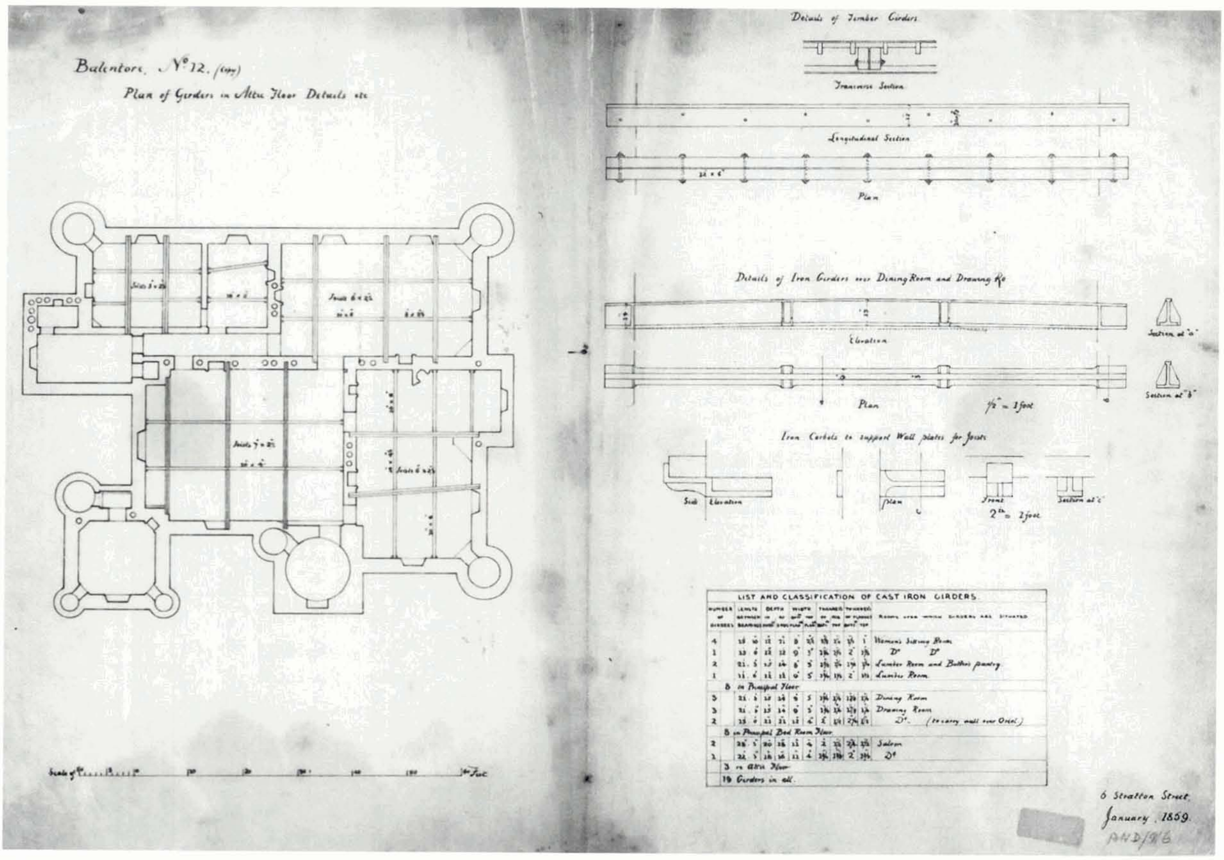


Illustration 85 Balintore House, Kirriemuir, Angus (1859) Plan and details of cast iron floor girders (Picture: RCAHMS)

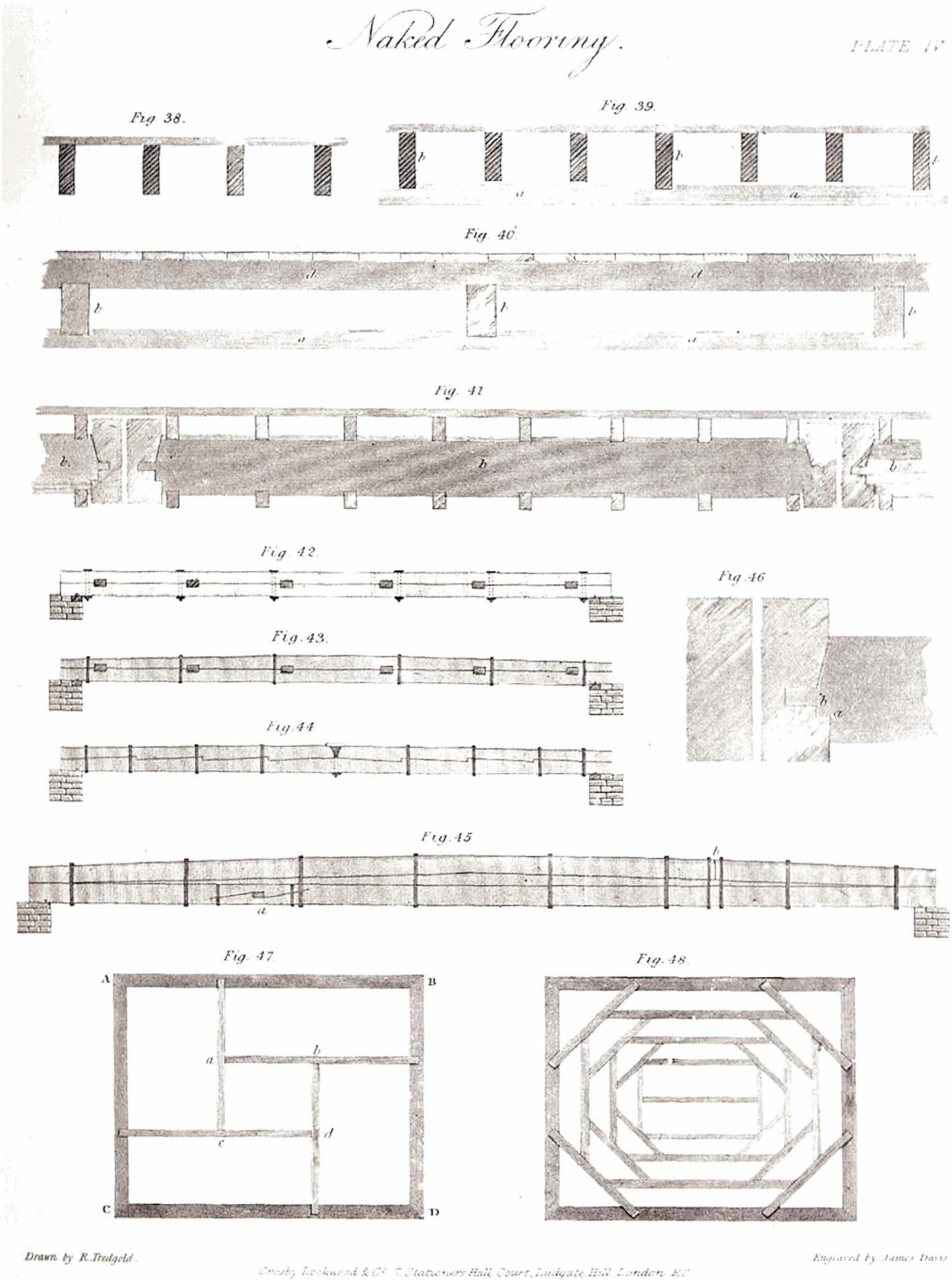


Illustration 86 Timber framed floor details. The elements of the floor are bridging joists, notched over supporting binding joists, with ceiling joists notched under. The bridging joists support wooden floor boarding and typically span between binders spaced 6' apart, the binders in turn spanning between girders at 10' centres. From tables based on Tredgold's formulae, for a 'normal' floor loading of 120 lbs/ ft² (5.8 kN/m²), girders of 'Yellow Fir' (probably Yellow Pine) spaced at 10' would be 15" deep and 16" wide for a span of 22'. The recommended warehouse floor loading was 360 lbs/ft² (17.2 kN/m²) (Tarn, 1886).

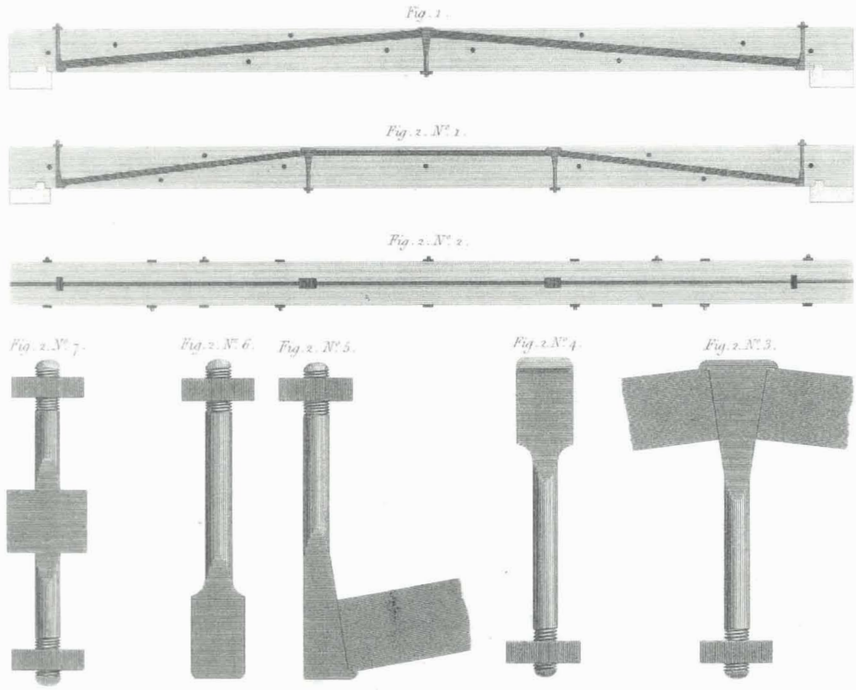


Illustration 87 Internally trussed timber beams (Nicholson, 1805)

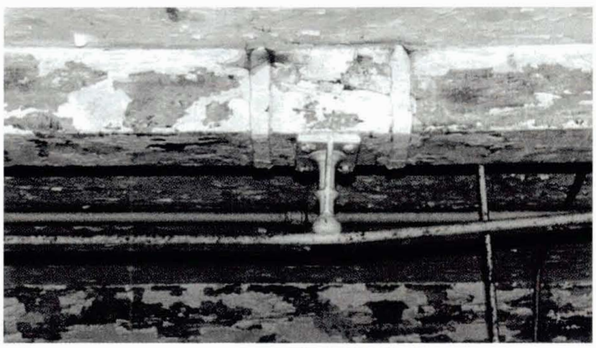


Illustration 88 Chapel Works, West Mill Montrose (c.1860) Externally trussed timber beams. Note the scarf joint to the timber beam above the spacer bracket (Picture: Mark Watson, Historic Scotland)

for signs of decay and also aided drying of the timber. For longer spans, internal trussing of either oak or iron would be fixed into grooves between the two halves of the girder (Illustrations 87 and 88). Modern tests have shown such arrangements to be structurally rather ineffective (Dawes, 1985). As early as the 1730s, the architect William Adam used timber beams trussed with wrought iron when inserting a floor at Yester House, East Lothian (Stancliffe, 1986).

For the framed floor over the 41' wide King's Library in the British Museum, completed in 1825, the architect Robert Smirke's first plan was to use cast iron girders trussed with wrought iron. However, the

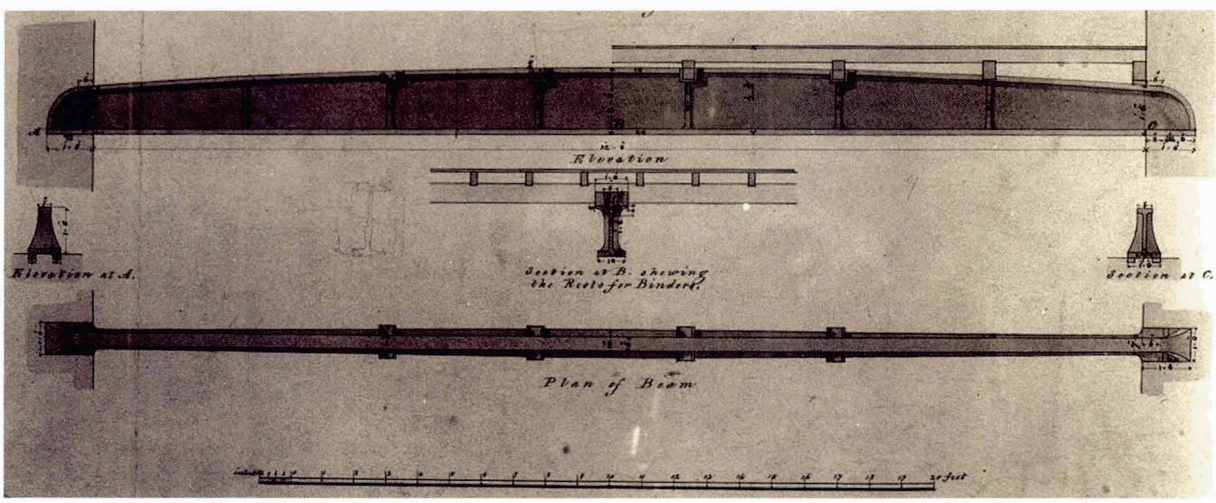


Illustration 89 United College, St. Andrews University (1846) Cast iron girders to the timber-framed former museum floor Architect William Nixon, cast iron girders by Blaikie Bros. (Picture: University of St. Andrews)

engineer and ironfounder John Rastrick persuaded him that trussing rods were not needed (Slade, 1995). Rastrick's cast iron girders were of an innovative design, with perforated webs to minimise weight. Smirke used cast iron girders again at the London Customs House, providing a pattern that other architects followed. A drawing showing one example has been found in Scotland, although opening up works have not been carried out to determine if the floor is built as drawn (Illustration 89). Generally, cast iron beams should be suspected in longer spanning floors from the period 1825 to 1860. The latest known example dates from 1894, hidden within the construction depth of a wooden floor in a public library in Ashton-under-Lyne.

By the mid-1850s, distrust of cast iron beams in building floors was fairly widespread after several building collapses (see 7.3.2). At a meeting of the Architectural Institute in Edinburgh in 1856, Thomas Davies gave details of proof-tests made for him on a variety of wrought iron girders made up of riveted angles and boiler plate (Davies, 1856). The tests had been carried out in the yard of an engineering works in Leith Walk owned by Mr Tod. Davies reported that Mr. Tod 'subsequently made many such beams for other parties, so that they have to some extent become known and used in this locality' (see Illustration 19).

In 1855, Robert McConnel patented a novel form of iron floor beam that was used in a significant number of Glasgow buildings (Illustration 90). The floor to the great hall in Rutherglen Town Hall, constructed in 1862 to the design of architect Charles Wilson, used McConnel patent girders of 34' clear span to support timber joists spanning 10'. Professor W J M Rankine of Glasgow University was consulted about the strength of the floor while the building was under construction. Taking crowd loading as 120 lbs/ft^2 (5.75 kN/m^2) with another 30 lbs/ft^2 (1.44 kN/m^2) for the weight of the floor, Rankine concluded from his structural calculations that the McConnel girders were far too weak. The Town Council resolved to prop the McConnel girders at mid-span by an additional cast iron girder supported on cast iron columns. The use of a cast iron girder was not in accordance with Rankine's advice, which had been to use a girder of malleable iron (i.e. wrought iron).

Wrought iron beams and girders were lighter than the equivalent in cast iron and, as its use in buildings increased, wrought iron gained the advantage in terms of cost too. In 1884 a London engineering contractor compared a wrought iron plate girder (with a 3/8" x 15" deep plate web and 3" x 3" x 3/8" riveted angle flanges), with the equivalent cast iron beam (Moreland, 1884). The wrought iron section weighed 44 lbs/ft (65 kg/m) and cost 11 shillings per cwt, compared to 133 lbs/ft (198 kg/m) and 7 shillings per cwt for the cast iron. From around this time cast iron beams and girders tended to be used mainly in situations where durability was required, such as lintels and in ground floors over basements.

In the latter part of the nineteenth century, steel was used in a number of city centre buildings. Columns of

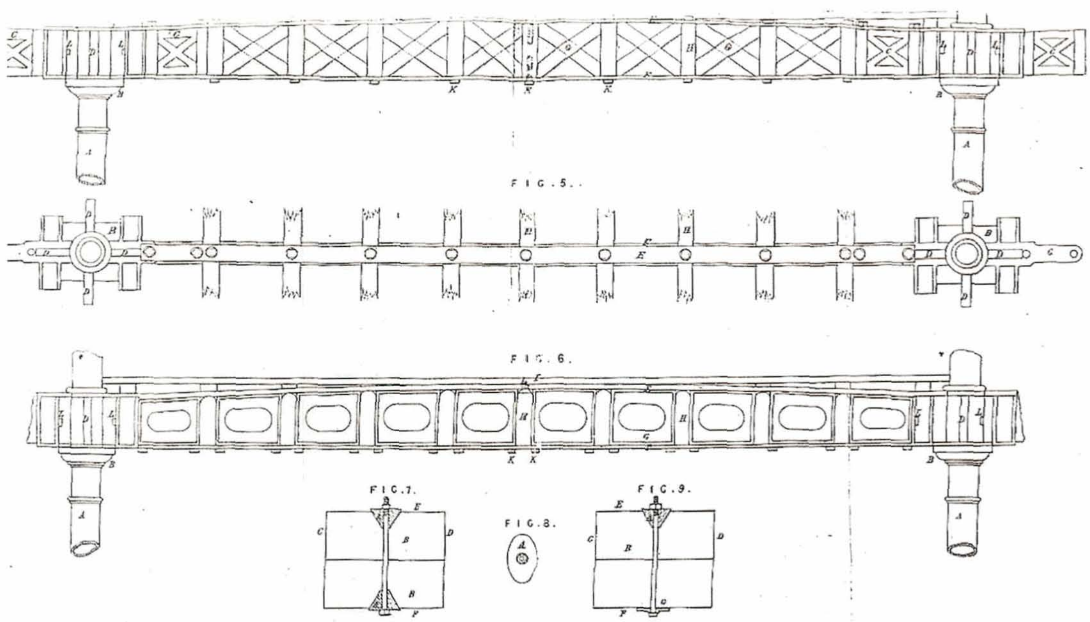


Illustration 90 McConnel patent girders. The girders have a top (compression) chord of wrought or cast iron and a bottom chord of wrought iron. Between the chords, the web of the girder is usually made with cast iron spacers held in place by vertical iron bolts. The supported timber floor joists pass between the web spacers, thus the girder is both hidden from view and protected from fire by a plaster ceiling. (Source: from McConnel R. of Glasgow, ironfounder (1855). 'Beams or Girders for Buildings &c' Patent number 1085)

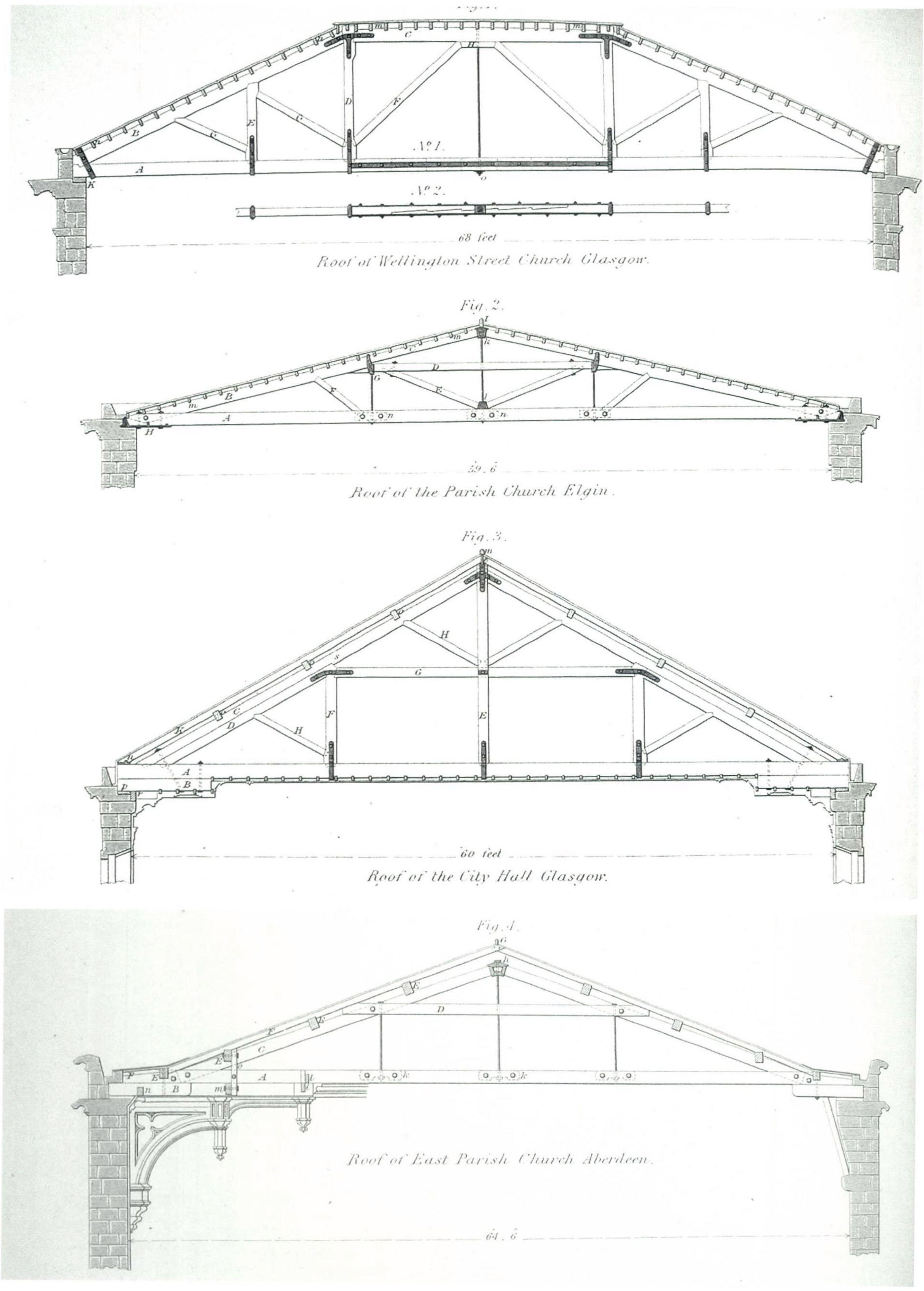


Illustration 91 Iron components in timber roofs. Cast iron shoes were sometimes used to protect timber ends bearing in masonry from decay. Iron sockets fitted to the ends of timber truss members enabled structurally more efficient connections to be made than with timber to timber joints. Ties of wrought iron were commonly used in place of timber (Source: Newlands 1880)

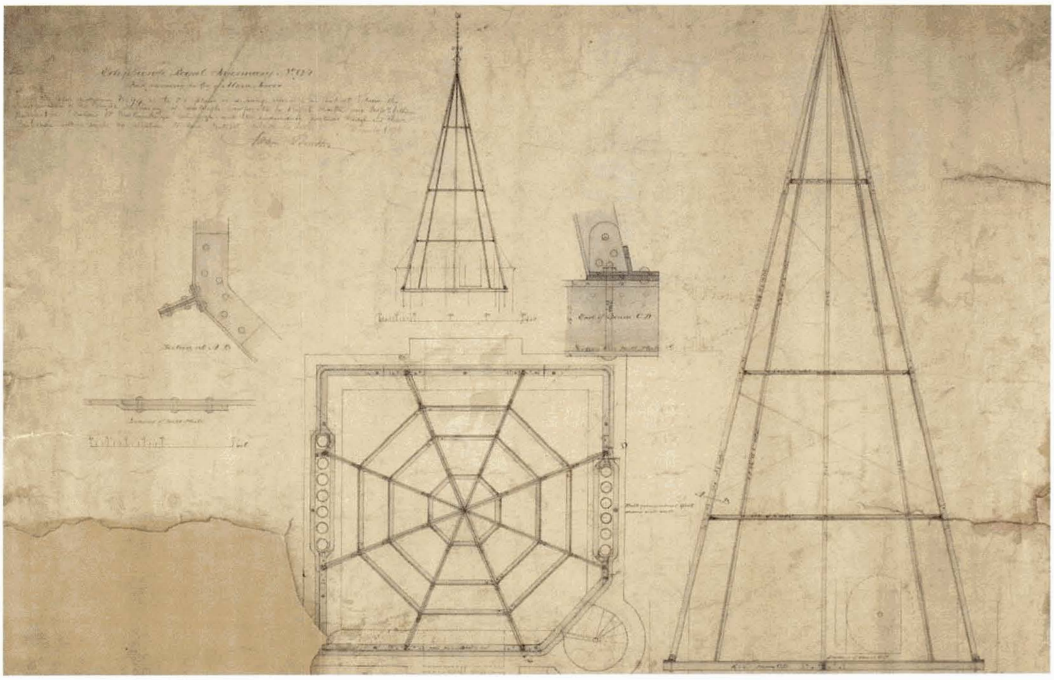


Illustration 92 Edinburgh Royal Infirmary (1874). Iron framing for Roof of Main Tower (Picture: University of Edinburgh, Department of Special Collections, Rowand Anderson Collection / The Drawn Evidence Copyright Lothian Health Board Archive)

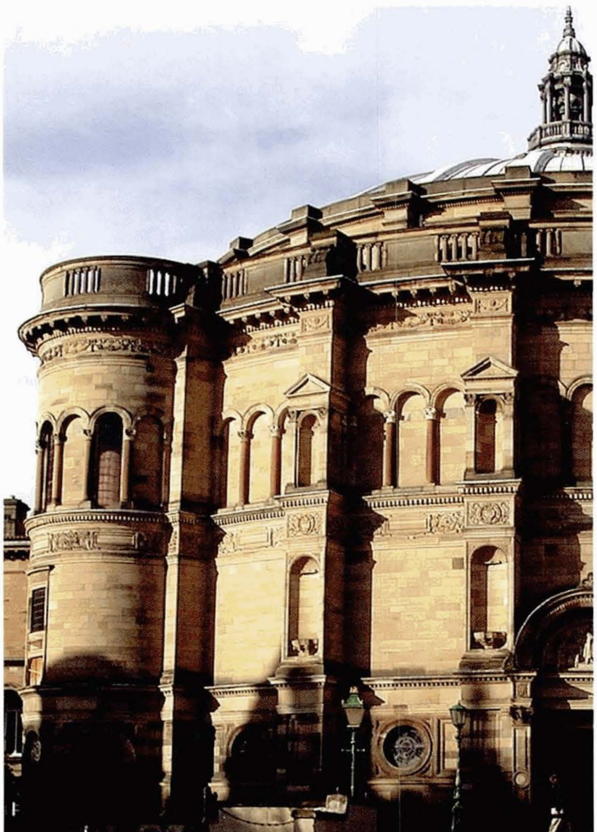


Illustration 93 McEwan Hall, Edinburgh (c. 1897) (Picture: T. Swailes)

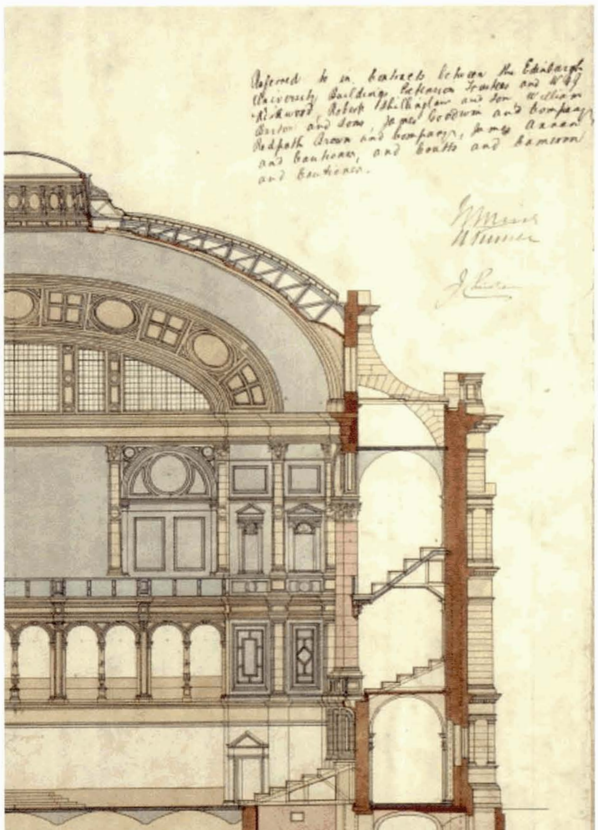


Illustration 94 McEwan Hall, Edinburgh (c. 1897). Section drawing (Picture: University of Edinburgh, Department of Special Collections, Rowand Anderson Collection / The Drawn Evidence)

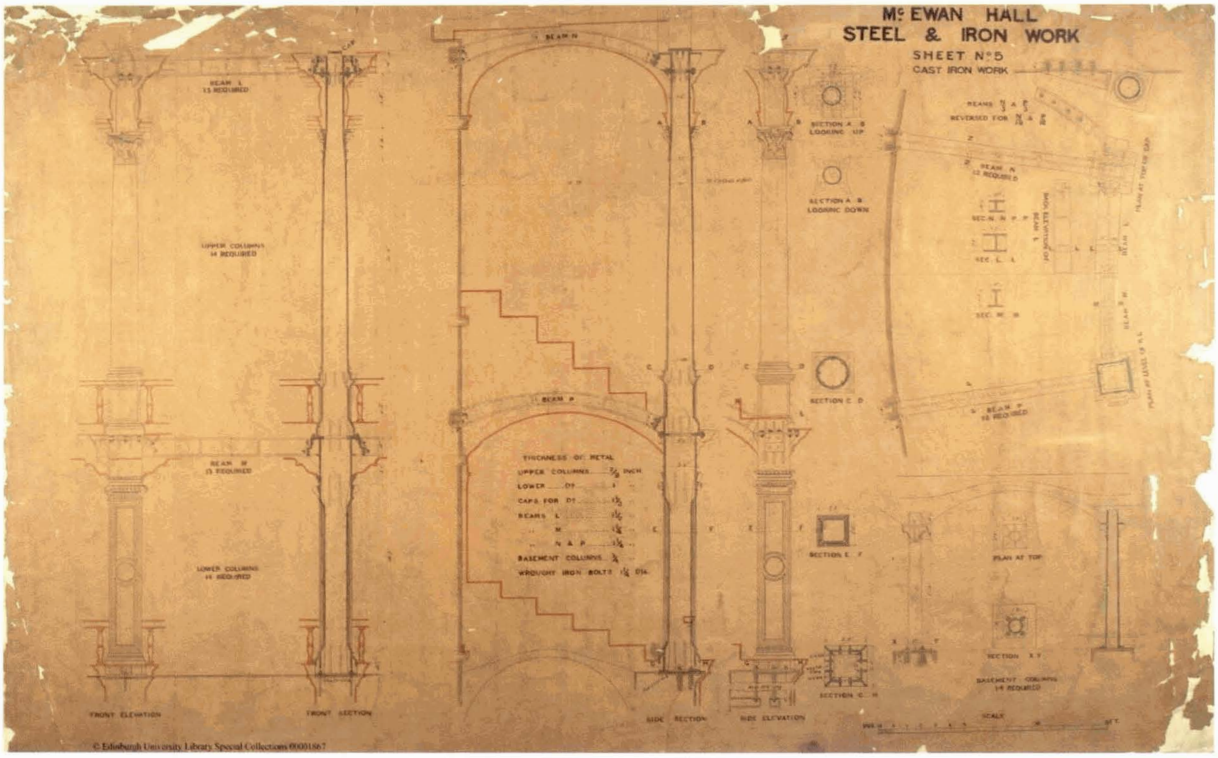


Illustration 95 McEwan Hall, Edinburgh (c. 1877) Ironwork details (Picture: University of Edinburgh, Department of Special Collections, Rowand Anderson Collection / The Drawn Evidence)

cast iron appear to have been superseded by steel, without a 'wrought iron transition' between. Some cruciform section columns built up from riveted steel angles were used in Jenner's Building in Edinburgh's Princes Street, completed in 1895 (Jackson, 1997). In Atlantic Chambers in Glasgow, completed in 1900 to the design of architect J. J. Burnet, steel beams slot through cast iron columns, between load bearing masonry walls. Edinburgh's Scotsman Building, completed in 1902, was the first commercial building in Scotland to use steel both for columns and for beams, with steel columns built in to at least one façade (Jackson, 1998).

For roofs, wrought iron straps and bolts or wedges assisted in the solution of jointing problems in the various forms of timber trusses introduced to Britain in the seventeenth century (Yeomans, 1992; Tarn, 1886; Newlands, 1857) (Illustration 91). The authors of the best-known carpentry manuals, Peter Nicholson and Thomas Tredgold, both worked in Scotland. Several drawings prepared by Nicholson for the University of Glasgow in 1806, including roof details, have been digitised for The Drawn Evidence project (see Section 9.8 and illustration 278).

Nineteenth century towers, spires and turrets are sometimes iron-framed, where previously timber would have been used (Illustration 92). Large span concert hall roofs, like the wrought iron roof to the Royal Albert Hall, evolved from the railway station roofs of the mid-nineteenth century (Swailes, 1997). The structure of Edinburgh's McEwan Hall combines old and new materials. Completed two decades after the architect R. Rowand Anderson submitted his competition winning design, the contract drawings show cast iron beams and columns framing the galleries (Illustrations 93 to 95). Parties to the Contract included the structural steelwork firm Redpath, Brown & Co. probably responsible for the roof structure. The brewer William McEwan funded the project.

3.2.6 Glasshouses and pre-fabricated iron buildings

The eighteenth century had seen a great upsurge in interest in the sciences, including botany. Conservatories or 'hothouses' were built to facilitate the study and enjoyment of plants from warmer climates. Iron could be formed into thin bars and was an ideal material for the glazing bars, or astragals, with advantages over copper in terms of strength and stiffness. Slender supports to the panes of glass offered the least obstruction to sunlight.

The Lanarkshire landscape gardener and writer J C Loudon, studied agriculture with an Edinburgh University professor while gaining practical experience with a landscape gardener based in Leith Walk (Gloag, 1970). In 1817, he published 'Remarks on the Construction of hothouses' in which he advocated curvilinear forms to take best advantage of sunlight. For the construction of such structures, he developed a wrought iron glazing bar that could easily be curved to the required shape. An early Scottish example was built by an ironmaster, George Mushet, in the grounds of his house in Dalkeith. This conservatory is very unusual, being of cast iron throughout; the glazing bars included (Illustrations 96 & 97 also illustrations 214 to 216). On a grander scale, there are some fine conservatories and winter gardens in Scotland's public spaces, parks and botanic gardens. Some have been refurbished, while others await a saviour (Illustrations 98 to 103).

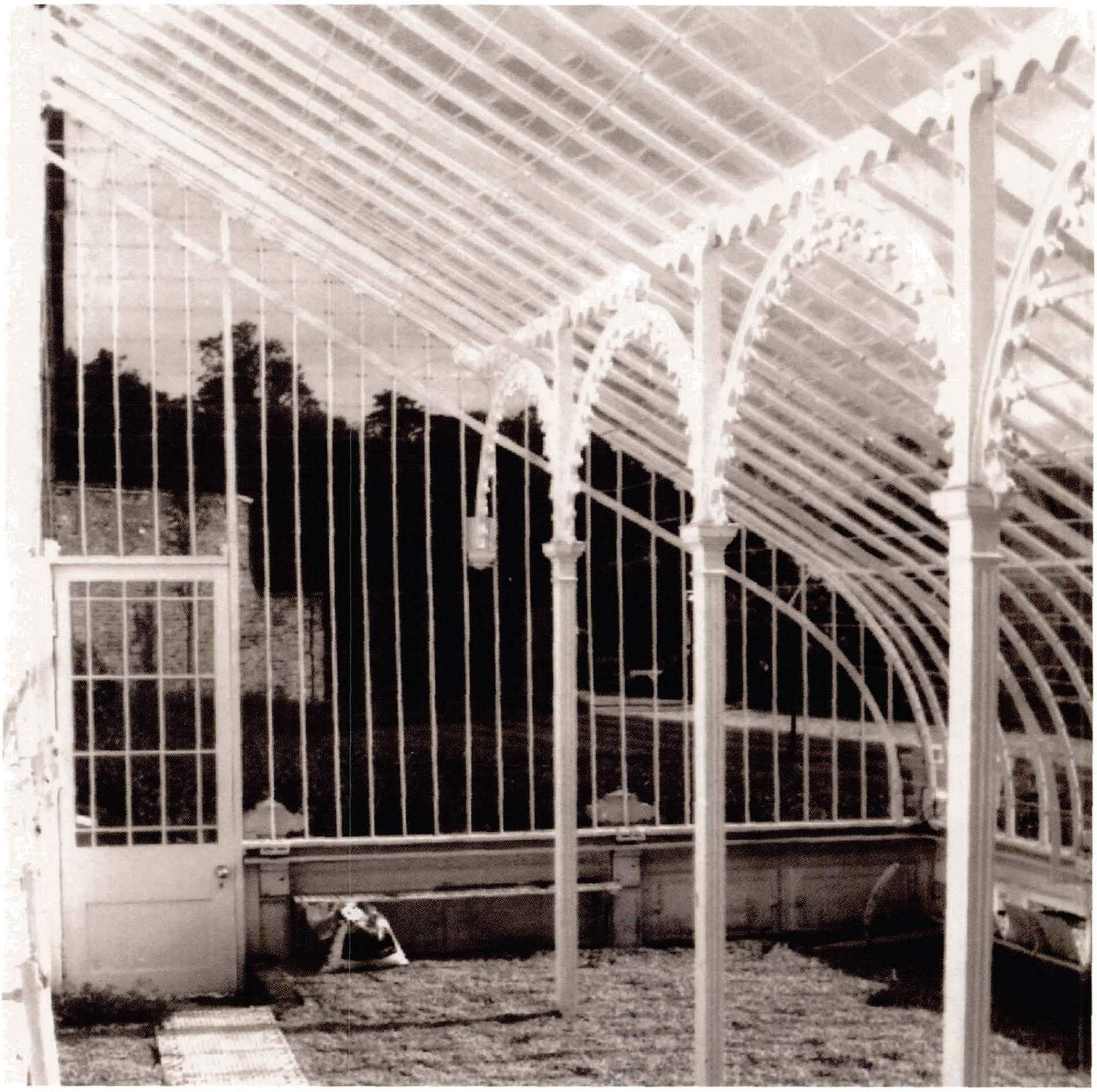


Illustration 96 Fairfield House conservatory, Dalkeith (c.1835) Internal view. It seems likely that all the parts were made in the foundry next door to George Mushet's house. This small but very fine lean-to structure has recently been restored. (Picture: T. Swailes)

Illustration 97 Fairfield House conservatory, Dalkeith (c.1835) Ironwork details (Picture: T. Swailes)

Illustration 98 Palm House, Edinburgh (c. 1858). External view (Picture: Royal Botanic Garden, Edinburgh)

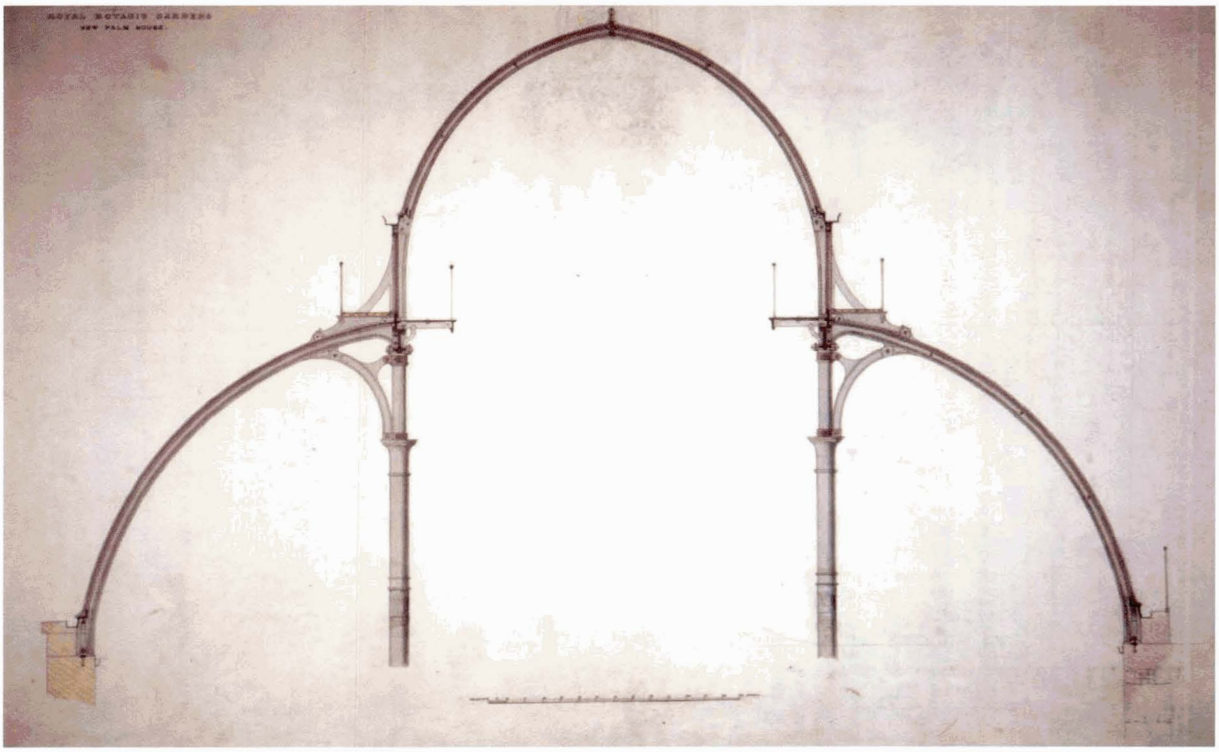


Illustration 99 Palm House, Edinburgh (c. 1858). Ironwork details (Picture: National Archives of Scotland)

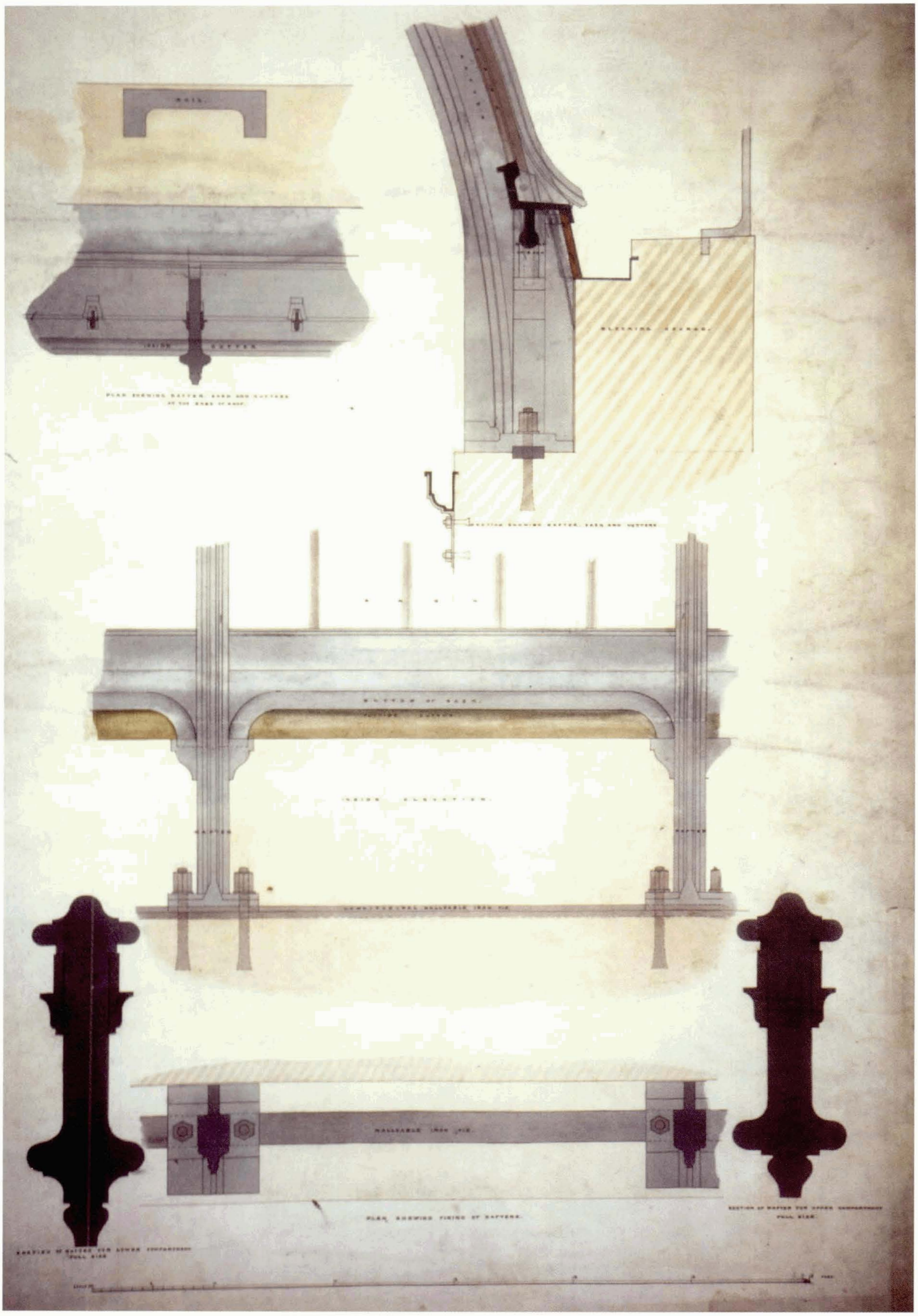


Illustration 100 Palm House, Edinburgh (c. 1858). Ironwork details (Picture: National Archives of Scotland)

Illustration 101 Tollcross House Conservatory, Tollcross Park, Glasgow (1858) The structure after restoration (Picture: Heritage Engineering, The Industrial Heritage Co, Ltd)

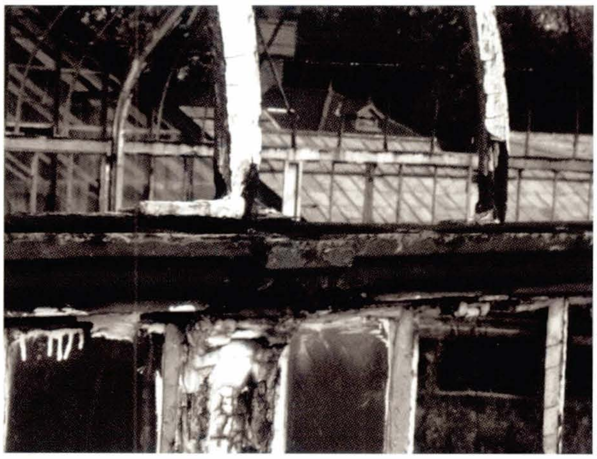


Illustration 102 Tollcross Winter Gardens, Tollcross Park, Glasgow (1858) Condition of the ironwork prior to restoration. Corrosion is most severe to the feet of the glazing bars (Picture: T. Swailes)

Illustration 104 Springburn Park Winter Gardens (1899). The dilapidated iron-framed interior in 2001. The filler joists to the gallery floors are likely to be steel (Picture: T. Swailes)

Illustration 103 Springburn Park Winter Gardens (1899). An early twentieth century view showing the bandstand, since removed (Source: Corporation of the City of Glasgow, 1914)

Illustration 105 The Manchester Art Treasures Exhibition Building (1857). It was the boast of the Edinburgh contractors, C.D. Young & Co., that 'the extent of their works, and their favourable position in the iron and coal districts, with a shipping port, enable them to undertake contracts to any extent, and at rates corresponding with the local advantages possessed' (Young, c.1863) (Picture: The Library of the Institution of Civil Engineers)

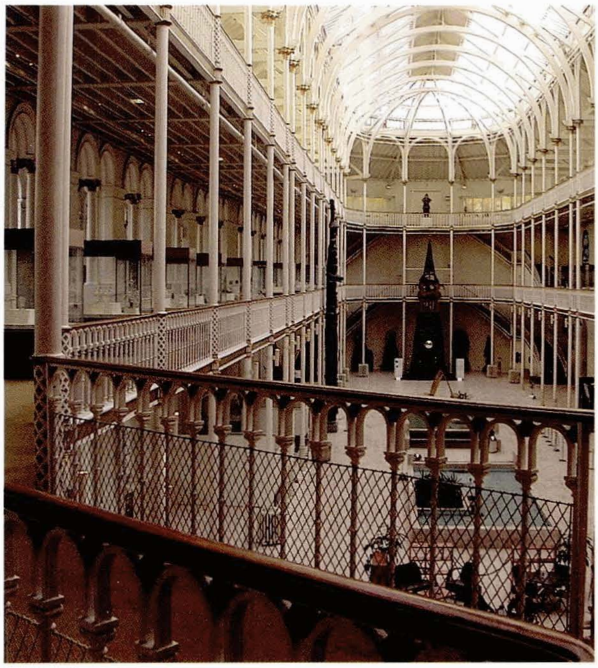


Illustration 106 The Royal Museum of Scotland (1861) General interior view. By 1870, the museum's great hall contained 'the largest collection in the World of the raw products of commerce'. Iron is used sparingly in the internal framing and in the roof, but its use was essential for the achievement of a slender and graceful structure (Picture: T. Swailes)

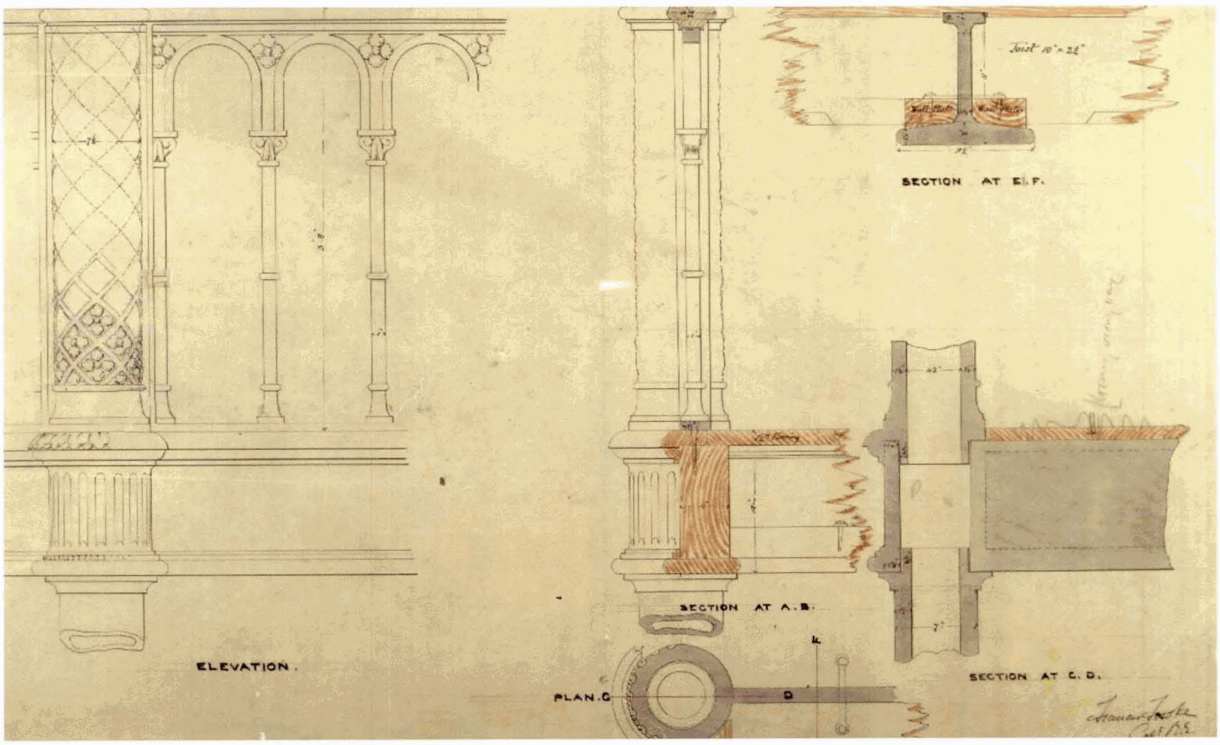


Illustration 107 The Royal Museum of Scotland (1861) Details of Columns and Balustrade on First Floor Level. A drawing of 1859, signed by Captain Francis Fowke, R.E. Concerns about load capacity led to replacement of some of the slender columns to the lower level gallery with steel tubular sections in the 1950s. The steel sections 'ring' on being rapped with the knuckles, while the thicker walled cast iron columns are very solid and unresponsive. (Picture: National Archives of Scotland/The Drawn Evidence)

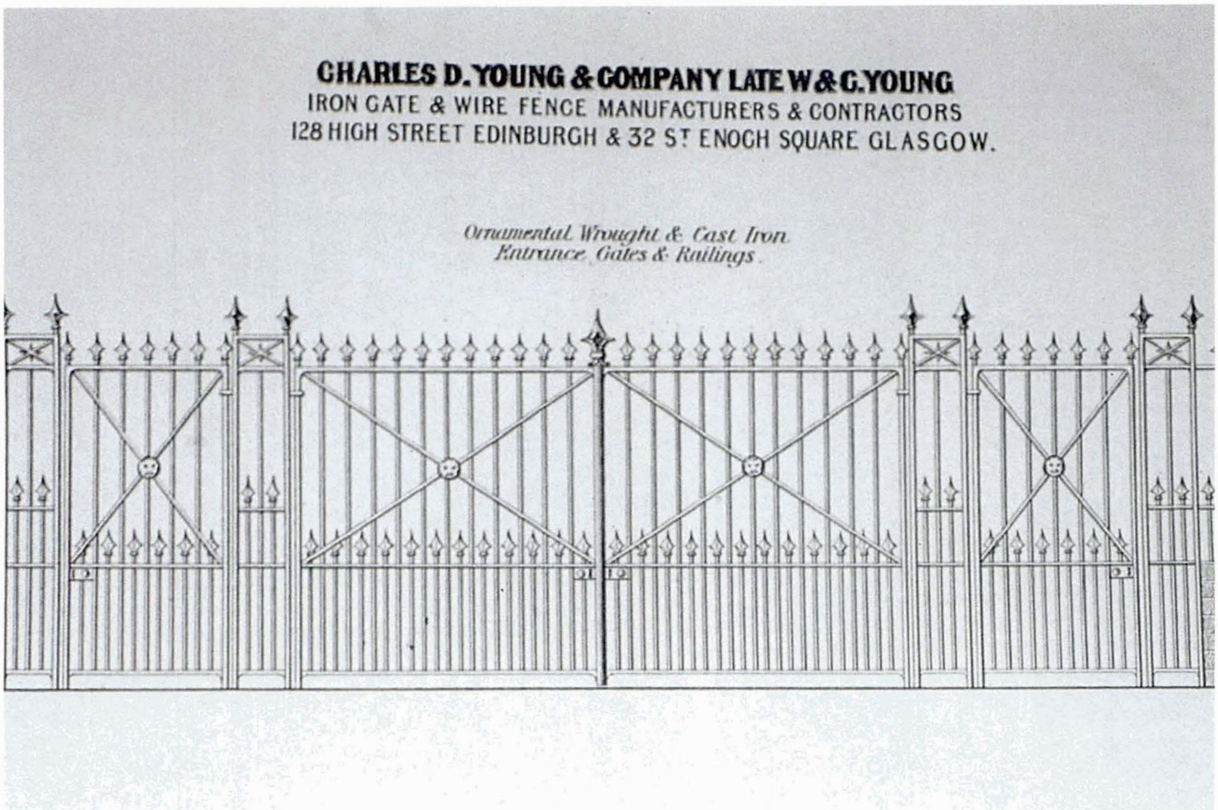


Illustration 108 Gates (Source: Young, 1848) (Acknowledgement: Library of the Institution of Civil Engineers)

Illustration 109 The Grahamston Gate
Gates provided an opportunity for the architectural iron foundries to display their talents. For this 20 ton triumphal arch the Grahamston Iron Company was awarded a Diploma of Honour at the Edinburgh International Exhibition of 1888. Afterwards it stood at the entrance to their works on Govan Avenue, Falkirk. Refurbishment and re-erection in 2002 was carried out by Carron Phoenix Limited as a tribute to the skills and artistry of the ironworkers of Falkirk (Picture: Historic Scotland)

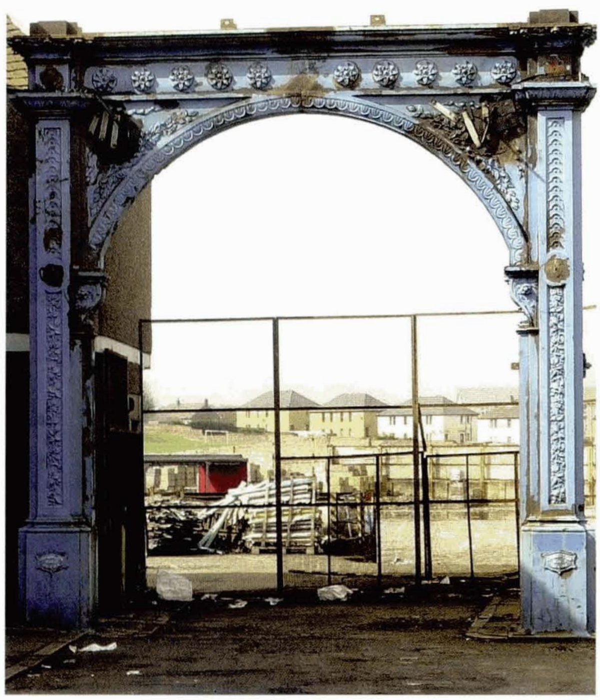


Illustration 110 The Grahamston Gate
Unsightly makeshift repairs to cracks, prior to conservation work (Picture: Historic Scotland)

Illustration 111 A bandstand from the catalogue of Walter MacFarlane & Co. This illustration may be compared with the structure at Magdalen Green, Dundee, shown in illustrations 2, 3 & 4.

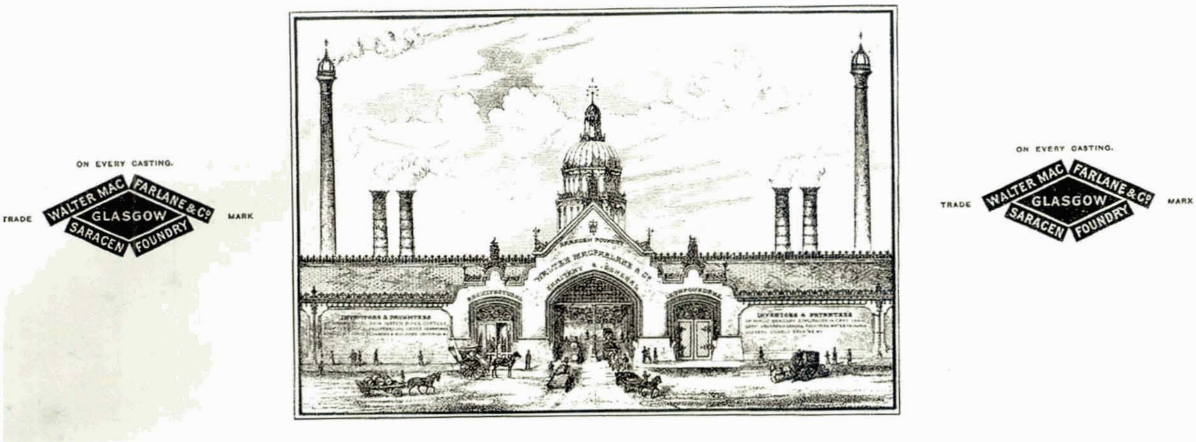


Illustration 112 Walter MacFarlane & Co's Saracen Foundry (Source: a MacFarlane catalogue, c.1907). The trademark shown is found on some castings.

For the building to house the Great Exhibition of 1851 in London's Hyde Park, pre-fabrication was used on an unprecedented scale. The structural ironwork contractors were Fox, Henderson & Co., whose Renfrew works managed by David Henderson made some of the structural components. A succession of exhibitions followed, an important part of which was to celebrate the 'industrial arts'. Edinburgh ironwork contractors C D Young & Company made the building for the Manchester Art Treasures Exhibition of 1857 (Illustration 105). The firm also provided the main building for London's International Exhibition of 1861, to the design of Captain Francis Fowke of the Royal Engineers. This building was the prototype for a permanent museum building in Edinburgh, now the Royal Museum, Chambers Street, also designed by Fowke, for which Prince Albert laid the foundation stone in October 1861 (see p274 and plate 22, Cassell's 'Old & New Edinburgh', Div'n IV) (Illustrations 106 and 107).

In 1850 Walter MacFarlane had founded the Saracen Foundry in Glasgow's East End, specialising in decorative iron castings (MacFarlane, 1882; Cox, 1991). The industry boomed in the second half of the nineteenth century, with central Scotland's foundries providing iron street furniture, shop fronts and architectural embellishments for most of Scotland's towns and cities (Illustrations 108 to 110). The Shire Album 'Cast Iron' draws liberally for illustrations on the c.1906 catalogue of McDowell, Steven and Co. and shows the vast range of foundry products (Fearn, 1990).

MacFarlane's and others supplied a range of small-scale pre-fabricated structures, such as drinking fountains, conservatories, and bandstands, of which many examples survive in Scotland (Illustrations 111 and 112). In the latter part of the nineteenth century, the export market throughout the British Empire and beyond for architectural ironwork and for kits for complete buildings was very considerable (Robertson, 1977; Herbert, 1978).

3.3 Bridges

3.3.1 Arch bridges

Design drawings dated 1774 by the architect and engineer Robert Mylne have been found for a 'chinese

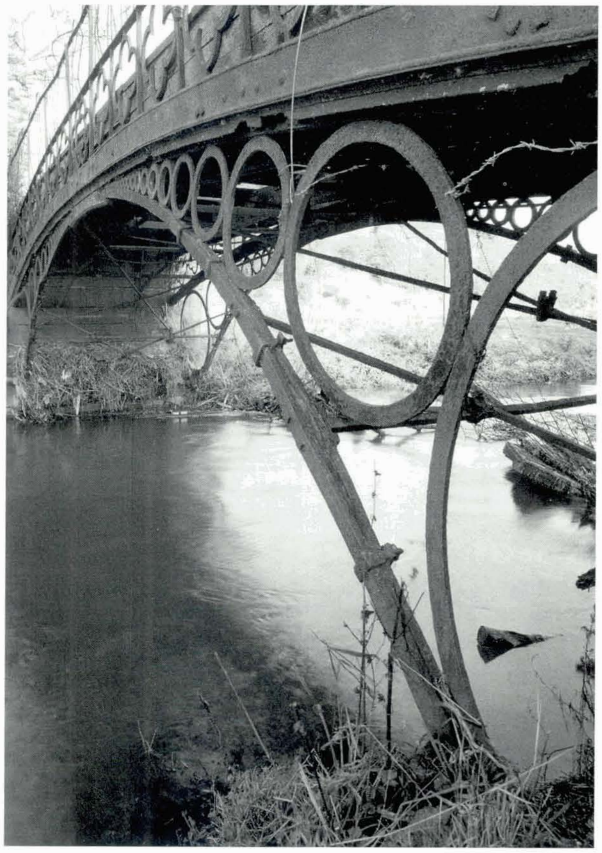


Illustration 113 Linlathen East Bridge, near Dundee (c.1804) (Picture: RCAHMS)

Illustration 114 Linlathen East Bridge, near Dundee (c.1804) (Picture: Roland Paxton)

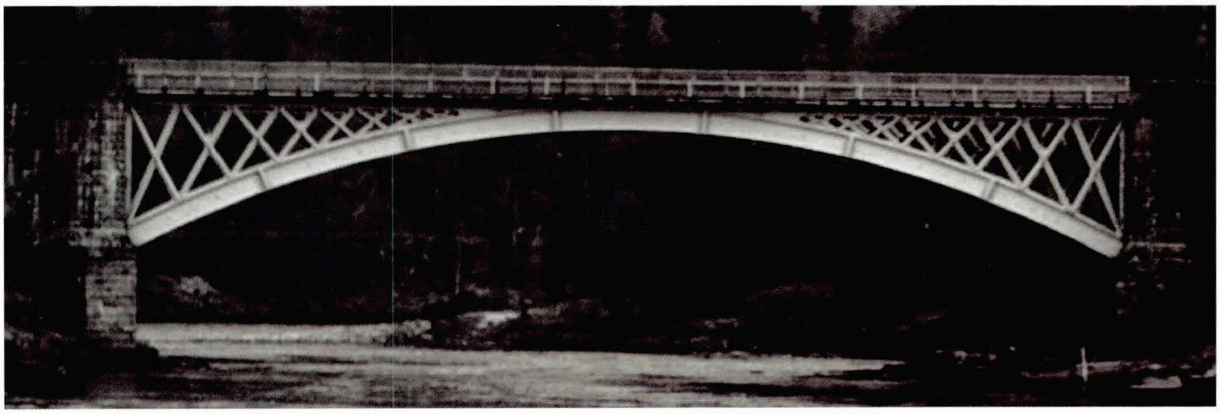


Illustration 115 Carron Bridge (1863) General view
Alexander Gibb, a pupil of Telford, was the engineer. The ironwork contractor was William McKinnon & Co. of Aberdeen, a general engineering company who at one time specialised in making plantation machinery. (Picture: Historic Scotland)

Illustration 116 Carron Bridge (1863) Structural ironwork details. (Picture: Mark Watson, Historic Scotland)

Illustration 117 Aqueduct over the River Almond carrying a feeder to the Edinburgh & Glasgow Union Canal (1818-21) General View
The engineer Hugh Baird used a series of open cast iron frames in the shape of voussoirs bolted together to form an arch either side of the trough (Paxton, 1980). (Picture: Roland Paxton)

Illustration 118 Aqueduct over the River Almond carrying a feeder to the Edinburgh & Glasgow Union Canal (1818-21) Detail (Picture: Roland Paxton)

bridge' at Inveraray, with light iron arch ribs to two 43' spans and decorative wrought ironwork above (Ruddock, 1979). It is not known if this bridge was ever built. Almost invariably iron arch bridges were of cast iron, a material superior to modern steel in terms of its compressive strength. Arched bridges for road and later for railway traffic continued to be built in cast iron well into the second part of the nineteenth century.

A candidate for the title of Scotland's oldest iron bridge is at Linlathen near Dundee (Illustrations 113 and 114). The hoops of diminishing diameter to the cast iron arch spandrels are characteristic of the Rowland Burdon Patent employed at Sunderland in 1796 with Thomas Wilson as engineer (James, 1979). Surviving Wilson bridges are widely distributed. Spanish Town Bridge in Jamaica was exported from the Walker's foundry in Rotherham, West Yorkshire and completed in 1801 (Blakiston, 1970). Another was erected a year later over the River Loddon in the grounds of the manor house at Stratfield Saye, Hampshire. Movement of one of the abutments caused cracking of the spandrels of the Stratfield Saye Bridge, which has recently been repaired and refurbished.

Other early cast iron bridges are Duchess Bridge at Langholm and its larger contemporary, the 151' 6" span Craigellachie Bridge (see Illustration 10), designed by Thomas Telford, over the Spey in Banffshire. Early wrought iron fixings and fasteners might be forged in Scotland, but from imported iron. For the main 184' laminated timber arch span to the Old Spey Bridge, Fochabers, the specification of Aberdeen architect Archibald Simpson called for the wrought iron and bolts to be '...best Swedish iron' (Day, 1987). Completed in 1832, Simpson's timber arches survived a little over twenty years before being replaced with more durable cast iron ribs.

Only a small number of cast iron bridges were erected in Scotland before 1840, although by that time Scotland was a major iron producer. John R Hume has prepared a list of cast iron bridges and identified James Abernethy & Co. as the leading Scottish contractor for cast iron arches in the 1850s and 1860s (Hume, 1978).

Carron Bridge, designed to carry both railway locomotives and road traffic, crosses the River Spey high above the summer water level (Illustrations 115 and 116). Closed to railway traffic in 1965, the bridge was the subject of a Public Local Inquiry in 1993 after Grampian Regional Council proposed to strengthen the

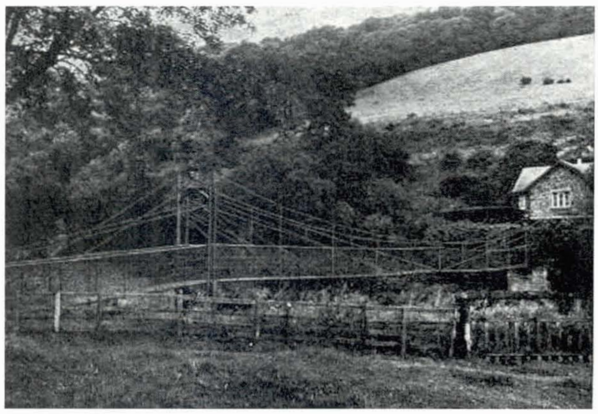


Illustration 119 Suspension Bridge by John Stephenson Brown (1817). With a span of 100 feet, a width of 4 feet and provision for 'tuning' the wire stays at the cast iron piers, the bridge was completed for a cost of £160. It was swept away by a flood in 1954 (Ruddock, 2002). (Source: 'Handbook of Structural Steelwork', Redpath, Brown & Co. Ltd, 1938, p458)

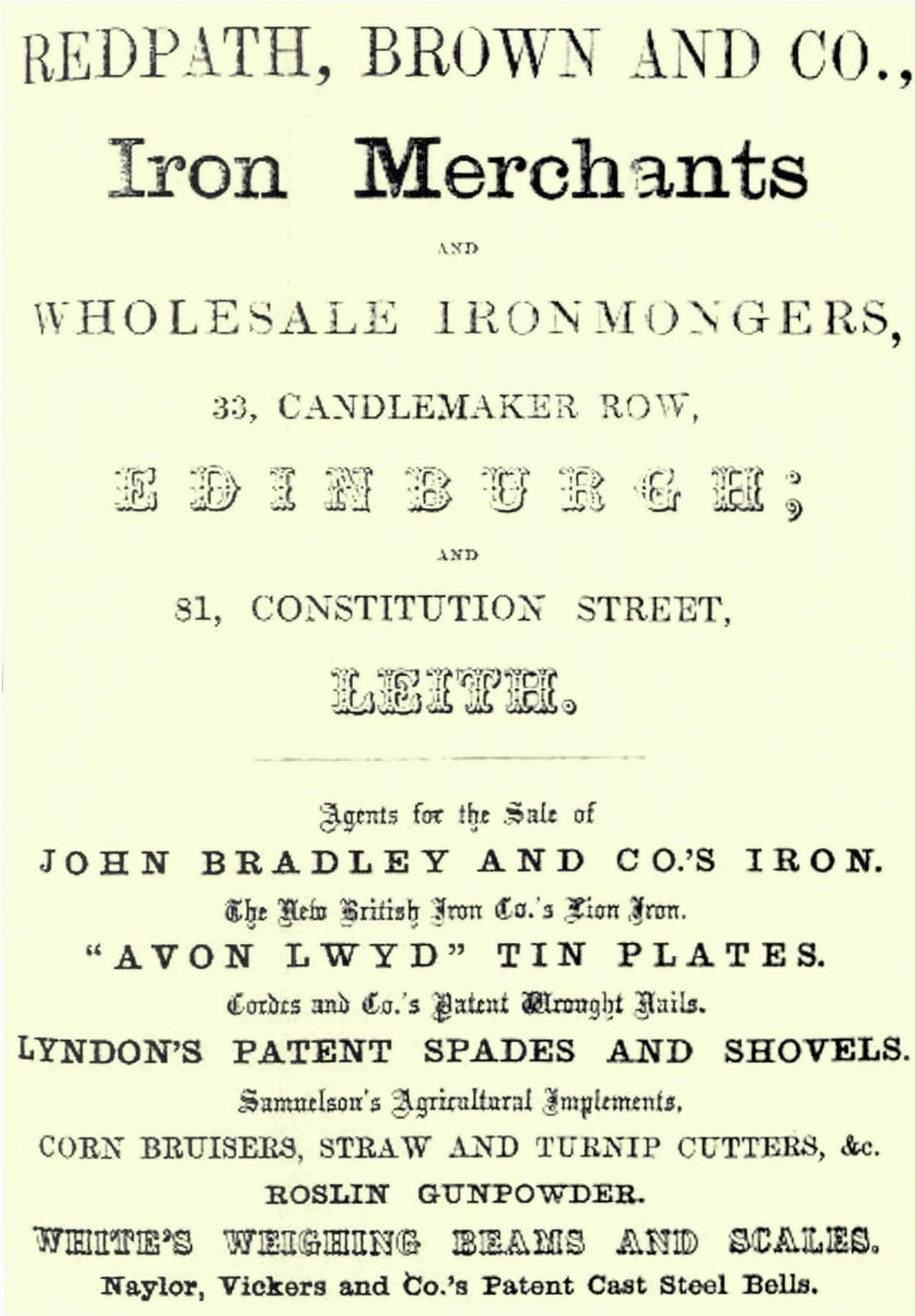


Illustration 120 Redpath, Brown & Co., Iron Merchants (Acknowledgement: Library of the Institution of Civil Engineers) (Measom, 1859)

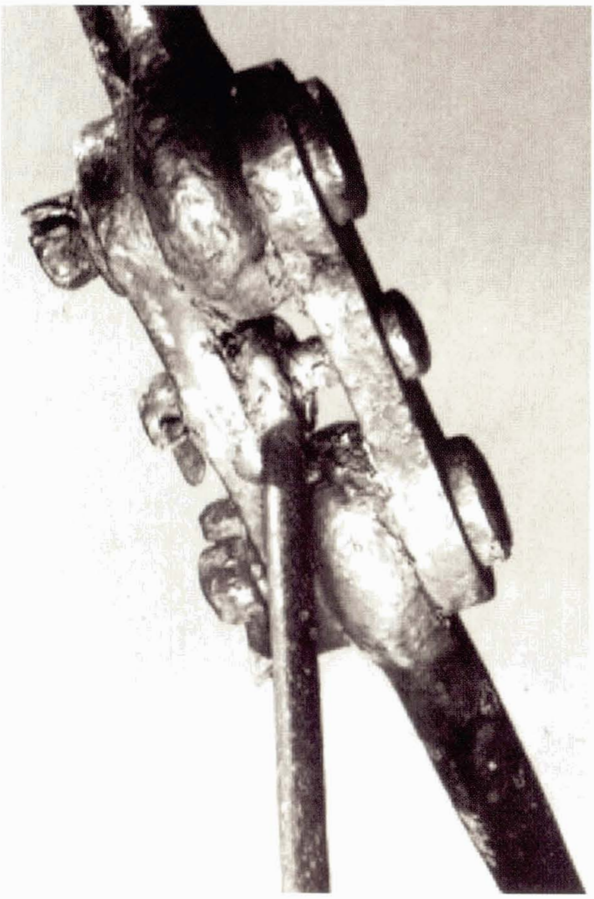


Illustration 121 St Devenick Bridge, Aberdeenshire (1837) Linkage unit (Source: Day, 1983)

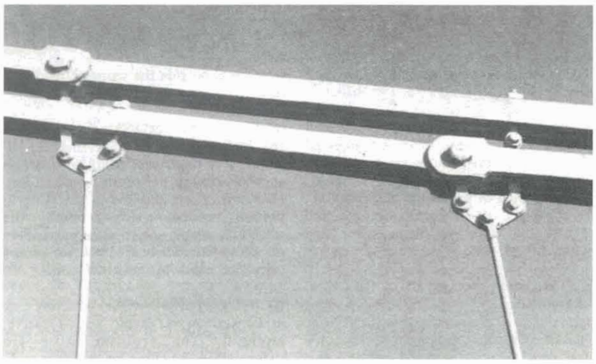


Illustration 122 St. Andrew's Bridge, Glasgow (1856) Suspension system (Source: Sutherland, 1988)

bridge by replacing its central cast iron arch rib with a pair of steel ribs of similar profile (Grampian Regional Council Department of Roads, 1994). The initial strength assessment of the bridge had been based on calculations only. After criticism of the calculations by an engineer appointed by Historic Scotland, the Inquiry was adjourned. A more thorough investigation was then carried out, involving full-scale instrumented static and dynamic load tests. Non-destructive testing techniques were employed alongside a close visual inspection of critical parts of the structure for defects. The fatigue limit for the cast iron was found to be close to calculated service stress levels, but no fatigue damage was found during inspection of the bridge. The bridge was proven safe for use without modification, except for the provision of a new deck. Load testing has confirmed the structural adequacy of other cast iron bridges where a more superficial

Illustration 123 Bridge of Oich, Abercalder, Invernesshire (1854) Prior to conservation
The bridge, built to the Dredge patent, had been deteriorating since it was by-passed in 1932.
It was taken into the care of Historic Scotland in 1996 (Picture: Mark Watson, Historic Scotland)

Illustration 124 Bridge of Oich, Abercalder, Inverness-shire (1854) The bridge, built to the Dredge patent, had been deteriorating since it was by-passed in 1932. It was taken into the care of Historic Scotland in 1996 and its refurbishment completed in 1997 led to a national civil engineering commendation in the 1998 Saltire Awards (Picture: Historic Scotland)

structural assessment might have led to unnecessary strengthening work or replacement (Blakelock, 1998).

The arch was favoured by engineers for bridging longer spans when there were no headroom restrictions. Clearance beneath would sometimes be maximised by placing the arch above the deck. This solution was used for an aqueduct near Edinburgh, with voussoir-shaped panels to the trough sides similar to Telford's earlier Longdon-on-Tern and Pont Cysyllte aqueducts (Illustrations 117 and 118).

3.3.2 Suspension bridges

Several early experiments in 'vernacular' or intuitive suspension bridge design were made by enterprising

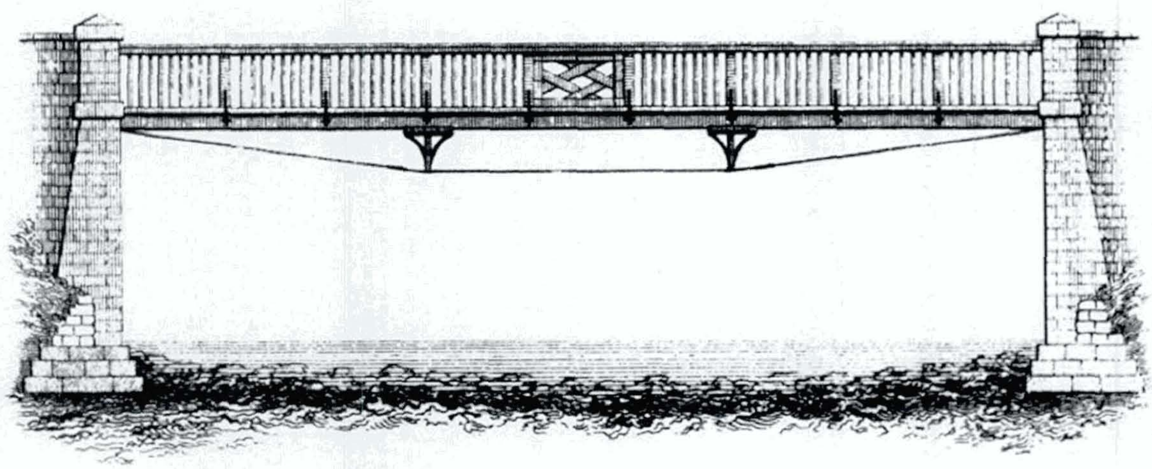


Illustration 125 Kings Bridge, Glasgow (1822) Illustrated in the Glasgow Mechanic's Magazine of 1824, the bridge was demolished in 1895 to make way for the Glasgow Central Railway (Boyce, 1996) (Picture: Mitchell Library, Glasgow)

Illustration 126 Roxburgh Viaduct Foot bridge (1850) (Picture: Crown Copyright: RCAHMS. Reproduced courtesy of JR Hume)

builders and blacksmiths in the Scottish Borders (Ruddock, 1990) (Illustrations 119 and 120). Captain Samuel Brown's 'engineered' Union Bridge was built over the River Tweed in 1820. Strengthened in 1902-03, and now with supplementary suspension cables, this is the oldest surviving road bridge of its type in Britain (Paxton, 1981).

Geoffrey Hay has recorded the details of several suspension bridges (Hay, 1986). A typical suspension chain and hanger arrangement comprises round wrought iron eyed bars with wrought iron flat connecting links and pins (Day, 1983) (Illustration 121). An alternative chain arrangement using flat eyed bars on the 1856 St Andrew's Bridge in Glasgow was first devised by Brunel for the Clifton Suspension Bridge, to enable longer links to be used (Sutherland, 1988; Pugsley, 1973) (Illustration 122).

Samuel Brown's Wellington Bridge, Aberdeen, completed in 1831, is still in service for pedestrians, but his bridge over the River Esk at Montrose, fared less well. In March 1830, with the bridge just a few months old, about 700 people were assembled on it to watch a boat race when one of the main chains gave way and the bridge collapsed, with considerable loss of life (Rendel, 1841). Owen William's reinforced concrete replacement of 1928-30 was a conscious imitation of its predecessors (Chrimes, 1996). Another bridge built by Brown, William Tierney Clark's Hammersmith Bridge over the Thames, caused concern in 1869 when used as a viewing platform for boat race crowds (Smith, 1992). A stiffer form of bridge devised by James Dredge had hangers inclined into the span, a hybrid of the suspension and the cable-stayed principles (Illustrations 123 and 124).

Around 1820 Robert Stevenson proposed a novel form of suspension bridge, with the roadway supported above the level of the chains, for a crossing of the River Almond near Edinburgh (Leslie, 1999). This bridge was not constructed, but in 1822 architect John Herbertson Jnr designed and built a bridge across Glasgow's River Kelvin on the 'suspension girder' principle (Boyce, 1996) (Illustration 125). The iron footbridge alongside Roxburgh Viaduct over the Teviot on the North British Railway's Kelso branch is an interesting variant (Paxton, 1981) (Illustration 126).

Illustration 127 Edinburgh & Dalkeith Railway, Braid Burn Bridge (1831) General view. Made and erected by Shotts Iron Co. in 1831, the bridge was conserved in 1983 by Lothian Regional Council and raised in level in 2001 (Picture: New Civil Engineer/Roland Paxton)

3.3.3 Girder bridges

Level girder bridges of cast iron were used for short spans where approach gradient and headroom restrictions made it necessary. Made and erected by the Shotts Iron Co in 1831, Braid Burn bridge, Duddingston, on the former Edinburgh and Dalkeith Railway, is a very early example (Paxton, 1983). Lothian Regional Council carried out conservation works in 1983 and raising works in 2001 (New Civil Engineer 2003) (Illustration 127).

Castings in one piece were either unsafe or impractical for longer spans, so long girders were cast in sections for bolting together at site, after the fashion of arch bridge ribs. Several railway engineers adopted the 'suspension girder' principle, in which the cast iron girder sections were trussed with wrought iron rods beneath, achieving spans in excess of 100'. A bridge of this type over the River Dee near Chester failed in 1847, due to a combination of several badly thought out structural details. In 1849 the influential 'Report of the Royal Commission appointed to inquire into the Application of Iron to Railway Structures', was published. The use of simple cast iron girder railway underbridges in Britain continued until 1882, when a bridge collapsed beneath a train at Inverythan on the Macduff and Turriff section of the Great North of Scotland Railway (Day, 2000) (Illustration 128).

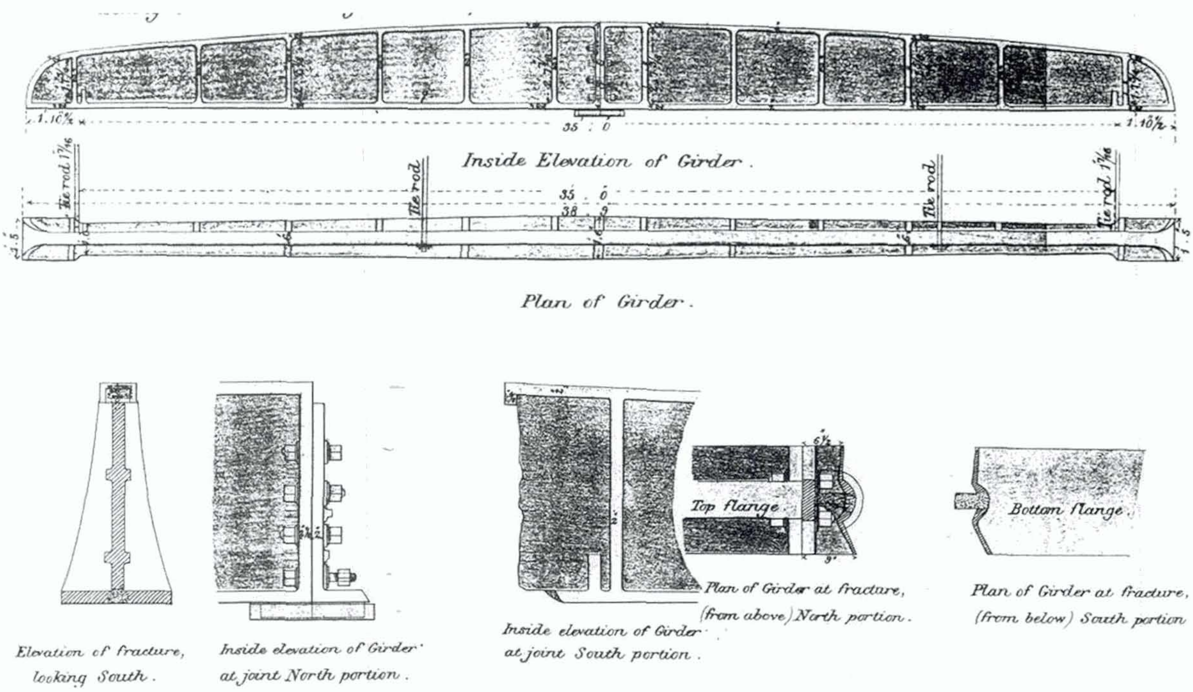


Illustration 128 Great North of Scotland Railway, Girder Bridge at Inverythan (1857)
Details of the fracture of a cast iron girder near a mid-span joint. The rails were laid on a timber deck between pairs of cast iron girders, each of clear span 38 feet 8 inches, cast in two halves and fastened together at the centre. The bridge had been in service for 25 years but the girders were not over-stressed according to the Board of Trade rules. With the benefit of hindsight, failure can now be attributed to fatigue and the propagation of a crack from a hidden defect near the base of the mid-span joint (Marindin, 1882, and Day, 2000) (Picture: The Library of the Institution of Civil Engineers)

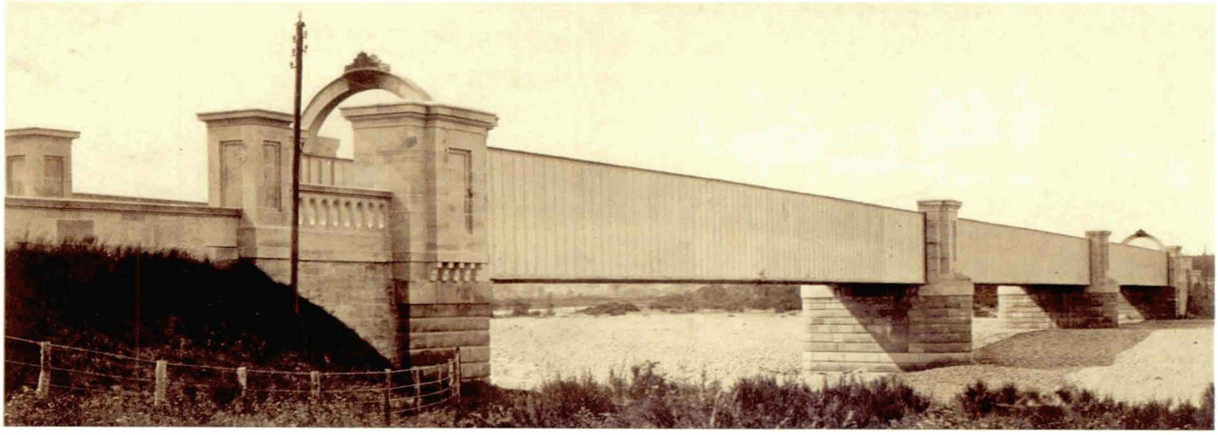


Illustration 129 Findhorn Viaduct (1858). Three 150 ft. spans. Engineer Joseph Mitchell, ironwork contractor William Fairbairn & Sons. From 'The Highland Railway: Photographs of Works', 1865. (Picture: The Library of the Institution of Civil Engineers)

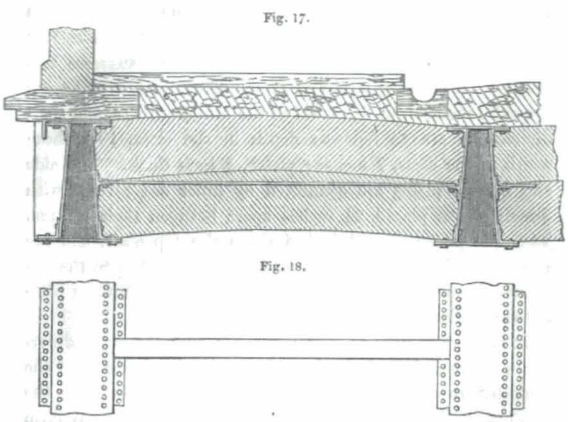


Illustration 130 Polloc & Govan Railway, Carmunnock Road Bridge (c. 1841) (Source: Dempsey, 1850) The bridge was erected by A. Thompson for the Govan Iron Works. Each tubular girder was 35 feet 3 inches long, 18 inches deep and constructed of 'the best boiler plate $^{3}/_{8}$ in. thick'. 3 in. × 3 in. × $^{3}/_{8}$ in. angles connected the flange plates via $^{1}/_{2}$ in. rivets at an unusually close $1^{1}/_{2}$ in. spacing. The tubes were filled with concrete to provide firm support to two courses of 9 inch brickwork, laid as near flat arches, over which the roadway was laid. Transverse ties of Low Moor (Yorkshire) wrought iron connected adjacent girders at mid-depth.

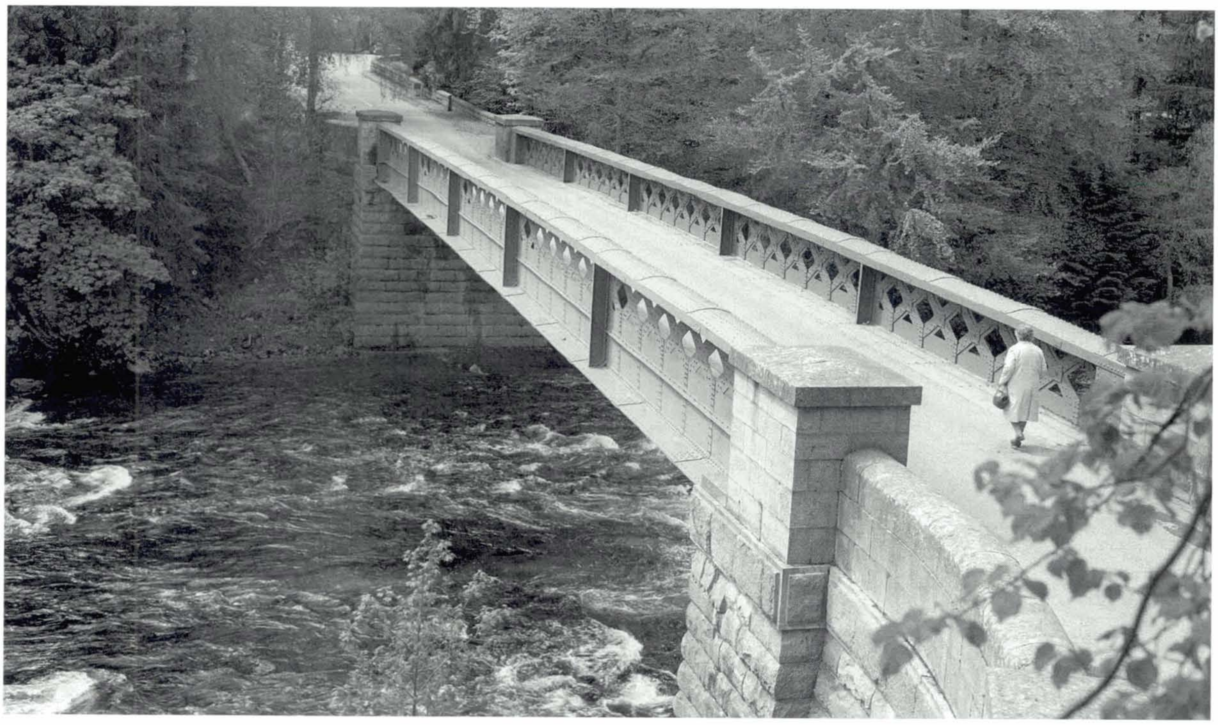


Illustration 131 Balmoral Bridge (1857) Designed by I.K. Brunel (Picture: RCAHMS)

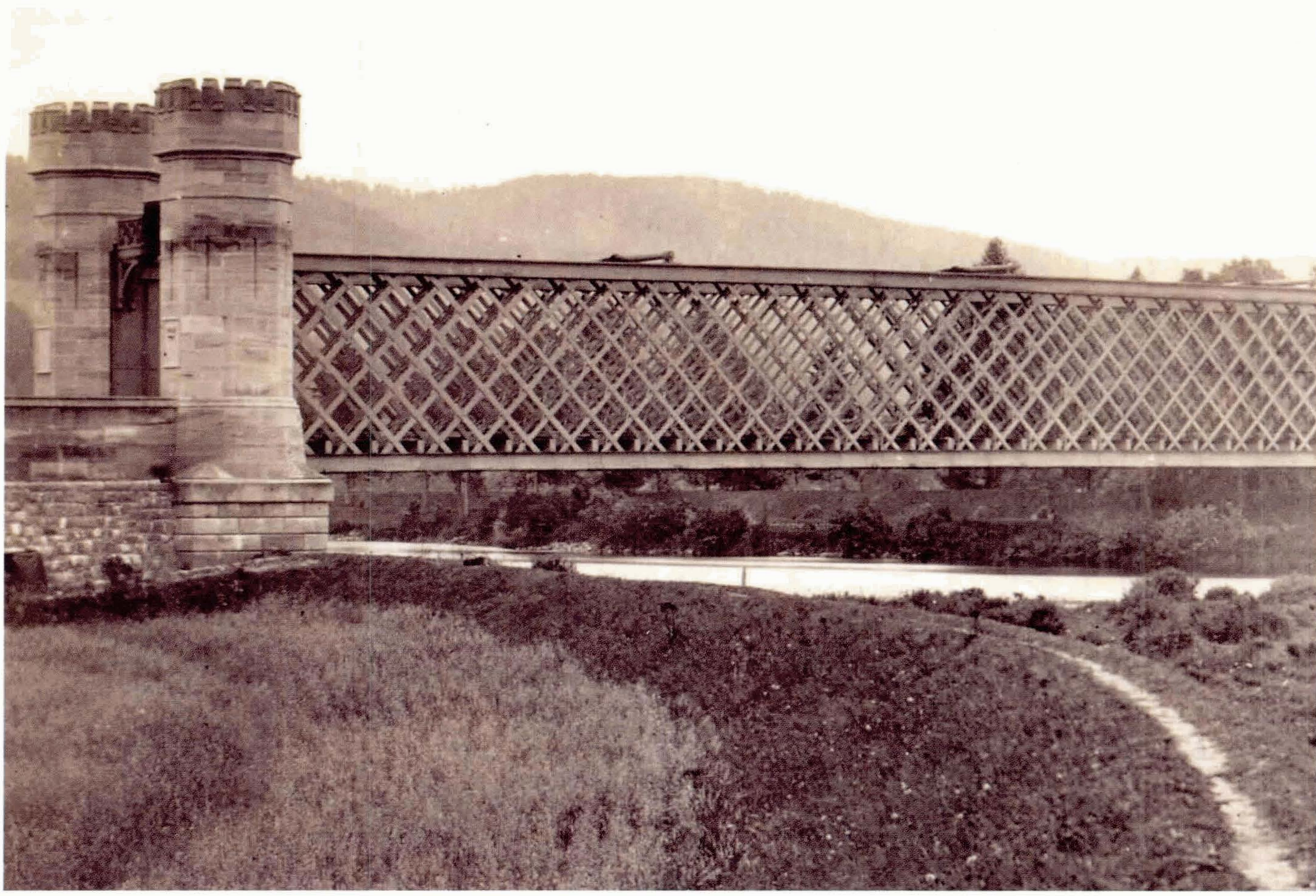


Illustration 132 Dalguise Viaduct (1863). Spans of 209 ft. and 141 ft. Engineer Joseph Mitchell, ironwork contractor William Fairbairn & Sons. From 'The Highland Railway: Photographs of Works', 1865 (Picture: The Library of the Institution of Civil Engineers)

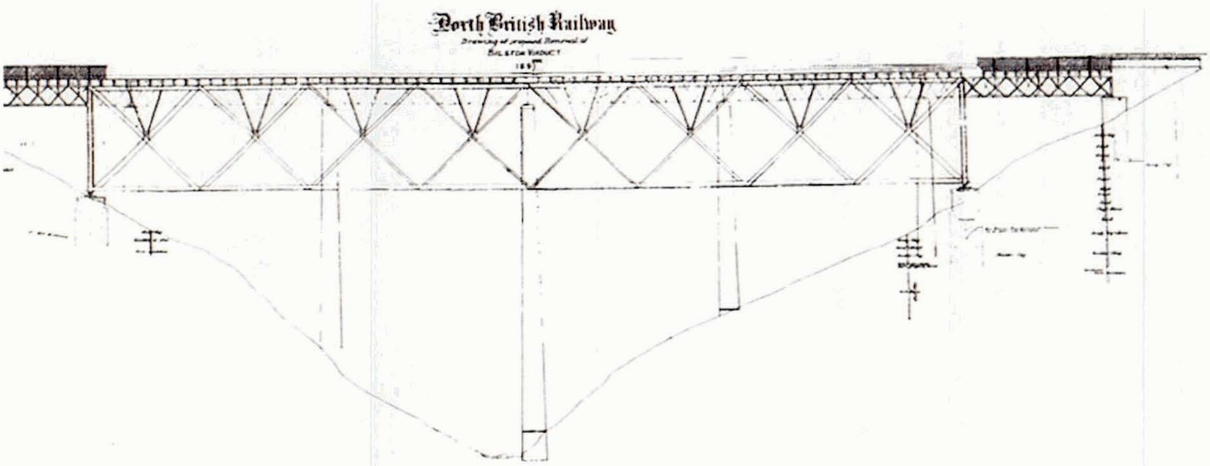


Illustration 133 Bilston Glen Viaduct (1872, 1892) . In 1892, the four central spans of Thomas Bouch's 6 span wrought iron truss viaduct were replaced with a single span steel truss of over 300 feet, with smaller side spans at either end. The recently refurbished structure now forms part of Midlothian's footpath and cycleway network. (Picture: British Railways Board (Residuary) Ltd)

A bridge constructed at Ardrossan in 1878 was fairly typical of the many cast iron girder railway overbridges still to be found in Scotland (Ministry of Transport, 1953). The bridge failed under an abnormally heavy load of 106 tons, as a ships crankshaft and bedplate were being drawn over it on a three-axle, twelve-wheeled trailer. The bottom flange tensile stress at failure (i.e. 'the modulus of rupture') for the centre girder was estimated at 8.7 tons/in^2 (134 N/mm^2) including a 10% allowance for impact. No significant flaws were found in the fractures to the girders.

For longer spans a more dependable alternative to the cast iron suspension girder was provided by William Fairbairn, a Manchester-based Scot. Fairbairn had diverse business interests, which included the building of iron ships and the manufacture of riveted wrought-iron plate boilers (Pole, 1877). In 1846 he patented a tubular form of riveted wrought iron girder and by 1870 his company had fabricated nearly one thousand bridges, principally for railways, with spans from 40' to 300' (Smith, 1994) (Illustration 129). An isolated example of a wrought iron tubular bridge girder bridge in Glasgow pre-dates Fairbairn's patent by 5 years (Illustration 130).

The single plate web girder had advantages over the two-sided box in terms of ease of fabrication, access for maintenance, and economy. The riveted wrought iron plate girder road bridge spanning the River Dee near Balmoral Castle, completed in 1857 and designed by I K Brunel, (Illustration 131) is one of the earliest of the type in Scotland (Buchanan, 1980). It was a natural progression from a solid web to an open web, although it is likely that the perforated web for Balmoral Bridge was provided for aesthetic reasons. Brunel dismissed early wrought iron lattice girders in characteristic fashion, giving evidence to the 1847-49 'Iron Commission', saying 'if I were obliged to make a bridge of a great span with a number of short sticks, that might be one mode of meeting the difficulty'. Joseph Mitchell has been credited with introducing the lattice form of girder to Scotland (Biddle, 1983) (Illustration 132).

The longer span box and lattice girders were superseded from the 1860s by various forms of trussed girder. In some early examples, cast iron was employed for truss compression members, with wrought iron used elsewhere. Many railway bridges have been replaced or strengthened during their lifetime, a good example being Bilston Glen Viaduct, built for the

Penicuik Railway in 1872 (Illustration 133). The 'double warren' parallel chord truss was one of the most popular forms in the last third of the nineteenth century, used by Thomas Bouch in his first Tay Bridge in 1879 and by William Henry Barlow in the side spans of its replacement, completed in 1887 (Shipway, 1987).

3.4 Ships

From the opening in 1834 of Tod & McGregor's shipyard on the Clyde for the construction of iron vessels, the growth of the Scottish shipbuilding industry owed much to the availability of cheap iron from Ayrshire and Lanarkshire (Wood, 1998). In the 1860s, composite construction using wooden hulls with iron framing was popular. Examples are the tea clipper Cutty Sark, built at Dumbarton in 1869 by Scott & Linton, and the Carrick (Illustration 104). Characteristic design features are wrought iron knee braces between the deck beams and the hull ribs to provide transverse stiffness, and cross-bracing to the hull sides to provide longitudinal stiffness (Scott, 1872) (Illustration 134). Amongst the earliest iron knees are to be seen in HMS Unicorn, built 1822-24 and now berthed at Dundee.

Steel, being stronger than wrought iron, offered significant weight savings but early steel suffered from quality control problems. The cause of steel was not helped by high-profile failures such as the flanged and riveted boiler plates of the Russian royal yacht Livadia (Beaumont, 1880). Steel deck beams were patented in 1859, and Scotland's first steel steamer the Windsor Castle was built in the same year (Duckworth, 1967). The famous Columba was made of steel in 1878 (Paxton, 1990). Of ships built in Britain in 1880, 18% were steel, the figure rising to 68% by 1886 (Matheson, 1886).

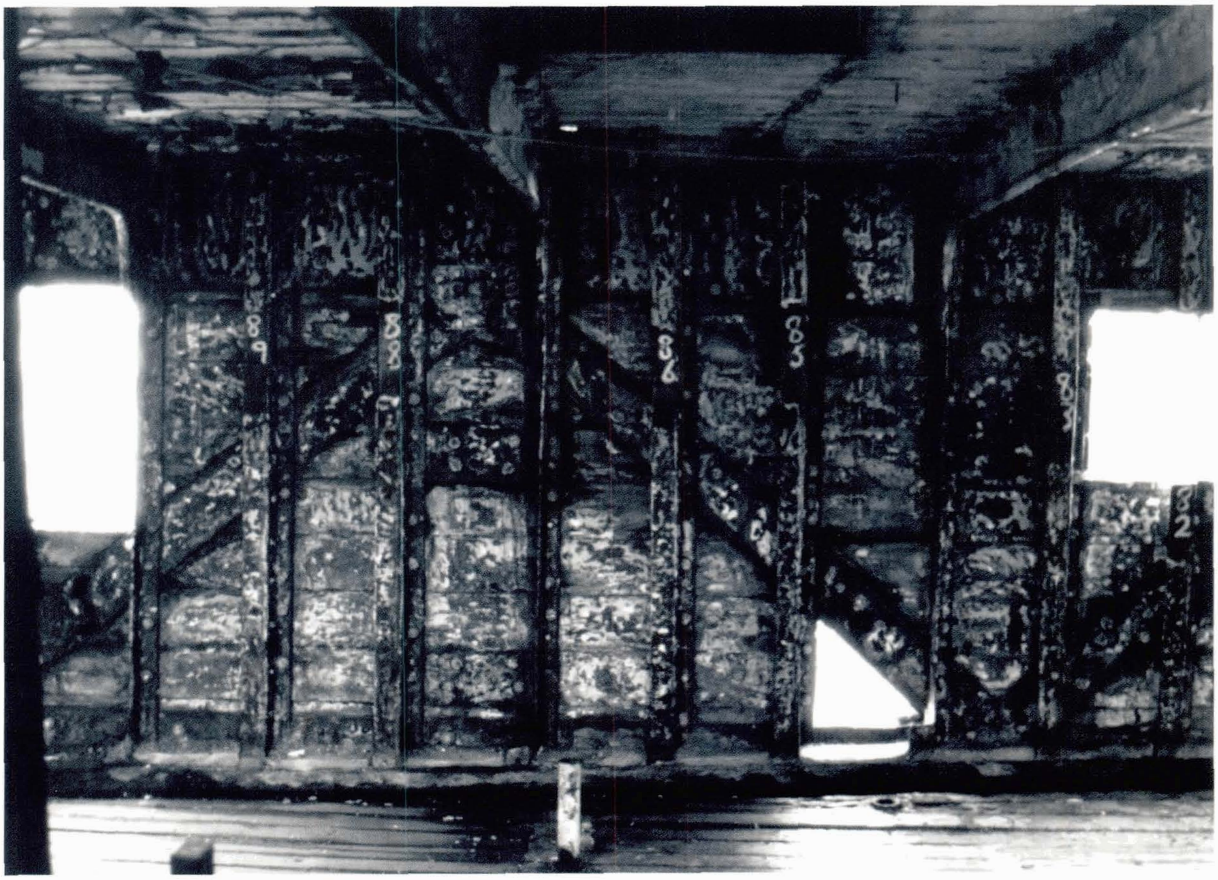


Illustration 134 The Carrick (1864). Braced hull and knee braced deck beams (Picture: T. Swailes)

4 STRUCTURAL APPRAISAL

4.1 General principles

'Perhaps the very first application of the art of structural engineering for conservation is being able to look at a very rundown, neglected and dilapidated building and to imagine what it might become with some effort, rather than immediately assuming that it has passed the end of its useful life and should be demolished' (Hume, 1997).

In a structural appraisal, information is gathered about the physical condition of an existing building and evaluated to determine if the building can safely meet the needs of its users. It is a process that should be carried out by or under the close supervision of a suitably experienced chartered civil or structural engineer.

The appraisal of old buildings, with or without iron framing, requires a good knowledge of their details and materials of construction. A specialist in the conservation and repair of cast and wrought ironwork may be consulted at the discretion of the engineer for a project, to inform his or her structural appraisal. For small iron structures outside the scope of the Building Standards (Scotland) Regulations 2004, their owners may choose to entrust inspection, conservation, and repair to an experienced contractor. The involvement of a chartered engineer in the assessment of a cast iron drinking fountain may not be necessary, for example, although each case should be considered on an individual basis.

Illustration 135 Park Bridge, Aberdeenshire (1854). Abernethy & Co, Ferryhill Foundry (Picture: RCAHMS, J.R. Hume)

There are several circumstances in which a structural appraisal may be required. Advice may be needed on the causes and structural significance of defects noticed by the owner or occupants of a building. Structural problems may be obvious after a severe storm or a fire, but their extent may be more difficult to establish. An engineer is often a key member of the professional team assembled for the appraisal of a non-domestic building prior to its repair, refurbishment, or conversion to a new use. Sometimes the decision to purchase or lease a building will depend on the contents of a structural report by a chartered engineer.

4.2 Surveys and inspections

A 'guide to surveys and inspections of buildings and similar structures' has been published by the Institution of Structural Engineers (IStructE, 1991). Useful sections deal with safety matters and with the legal aspects of survey and inspection work. Warnings are given against the careless use of the term 'structural survey', which is understood by the house buying

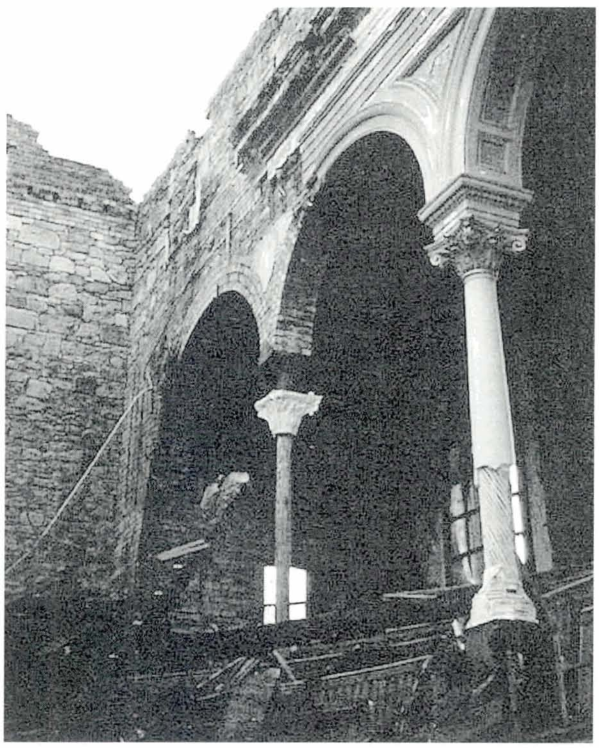


Illustration 136 Langside Hill Church, Glasgow (1896) Cast iron columns beneath lath and plaster. The building is now a restaurant (Picture: Neil Ross, Historic Scotland)

Illustration 137 Gourock Rope Works (1866) Partial floor collapse (Picture: Malcolm Watters, Historic Scotland)

public to involve an assessment of far more than just the load-bearing elements of a building. The term 'survey' is associated with measurement and recording activities, while the term 'inspection' implies examination and evaluation.

Advice on assessing the risks associated with the inspection of traditional structures has been published by the Health and Safety Executive (HSE, 1990). It should be noted that this and much other published guidance pre-dates the Construction (Design and Management) Regulations 1994 (and Approved Code of Practice), which define the responsibilities of designers, contractors and building owners for safety.

The purpose of site survey and inspection work is to obtain sufficient information about a building to enable a satisfactory structural appraisal to be carried out. Although the main source of information is the building itself, the more information that can be gleaned from documents or existing drawings the better. Iron bridges are quite often marked with a date and makers details but this is less often the case with buildings (Illustration 135). In any case, plaques or date stones may mislead. Similarly, drawings do not always present a true picture of what was built or how it may have been altered. Section 9 of this guide contains information of use when researching a building.

In a conservatory, all of the structural elements may be iron, but in most buildings iron will be present alongside other materials. Factory and warehouse buildings often have a visible skeletal frame of iron, steel or timber within external masonry walls. In contrast, in nineteenth century residential, commercial and institutional buildings, iron supports may have been concealed to maintain an illusion of more traditional construction (Illustration 136). A search of archival sources for information about constructional

Illustration 138 Larchfield Works, Dundee (1865)
High level inspection of fire damage
(Picture: Mark Watson, Historic Scotland)

Illustration 139 Larchfield Works, Dundee (1865)
The interior, destroyed by fire
(Picture: Mark Watson, Historic Scotland)

details may help the advance planning of any opening up works.

Site survey work should be led by an experienced person who, if working alone, especially in an empty or partially empty multi-storey building, should set up a system of 'reporting in' at regular intervals. Before entering a building it is necessary to walk around the outside to become acquainted with its general layout and condition and to identify any hazards, such as loose masonry at high level, that may render entry to the building unsafe. The order of priority in making an internal inspection is to first of all identify any risks to personal safety and to eliminate them or devise means of avoiding them, and only then to make an inspection of the structure. Detailed inspection and recording work should be done while stationary, as while walking it is best to pay attention to where you are going, and to nothing else.

The upper storeys of a building may be empty and dilapidated and possibly inaccessible because stairs are in an unsafe condition or missing. Ground floor tenants may be oblivious to a leaky roof and defective roof drainage. Floors that look safe when viewed in poor light and on a dry day should be inspected carefully from below before they are trusted. Water is the biggest cause of structural problems in semi-derelict buildings and, given the right conditions, timber joist ends will rot quickly in damp masonry. Wrought iron or steel joist ends in filler joist floors may suffer from severe corrosion. Brickwork arch floors can lose their integrity through the leaching out of mortar from brickwork joints (Illustration 127).

Initial survey work generally takes the form of a visual inspection, though suitable preparations can be made beforehand if the need for opening up works is established ahead of a first site visit. A few engineers supplement their basic kit of site boots, hard hat, overalls, torch, measuring tapes, callipers, spirit level, plumb line, a few small tools, sectional ladder, camera, pad, pencil and paper with a small arsenal of more specialist equipment in the boot of the car.

Most parts of an iron-framed building may be exposed and measurable, though not always readily accessible. Inspection and recording must be carried out in a systematic manner to ensure that no important features are overlooked. A simple ladder or access platform may be sufficient for safe access internally but scaffolding or a hydraulic mobile access platform (a 'cherry-picker' or a 'scissor-lift') may be necessary to gain access for external inspection at high level (Illustrations 138 and 139). A remotely sited mobile access platform may be useful to enable access to be gained to higher levels over obstructed lower levels (Illustration 140). Specialists in rope-assisted access using climbing techniques are sometimes employed,

Illustration 140 Larchfield Works, Dundee (1865) Debris after a destructive fire includes a typical cast iron rafter with seating for timber purlins (Picture: Mark Watson, Historic Scotland)

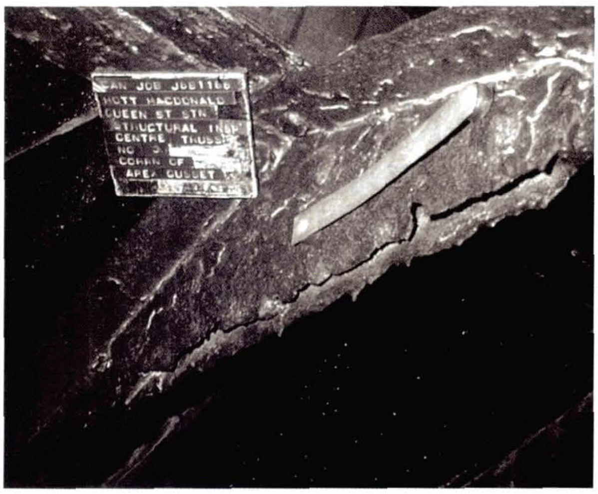


Illustration 141 Queen Street Station, Glasgow: Main train shed roof (1880) Corrosion of roof apex gusset. Close-up, 'tactile inspection' is necessary for wrought iron in particular, as the extent of corrosion can vary greatly between adjacent parts of a structure. Repairs made. (Picture: CAN/Mott Macdonald/ Network Rail)

Illustration 142 Clarence Mill, Bollington, England (1854) Opened up beam-column connection (Picture: T. Swailes)

such techniques being the province of trained experts only (Illustration 141).

Opening up works may be carried out to determine typical floor construction details, beam profiles and bearing and connection details and to obtain samples of materials for testing. Opening up might require listed building consent but may, subject to the necessary approvals, be accepted as necessary disturbance. Explanations may be sought at specific locations for surface cracks or signs of corrosion, although unnecessary destruction of original finishes and construction must be avoided. The possibility of encountering hazardous materials should be considered in a risk assessment. The work should be done by a skilled worker, with ease of subsequent re-instatement in mind and under the direction of the project architect or engineer, as appropriate (Illustration 142). Useful general advice is contained in an English Heritage leaflet, '*Investigative work on historic buildings*'.

4.3 Structural adequacy

Safety is the main criterion of structural adequacy, with strength, stability, robustness, and fire-resistance all considered in the appraisal of a building. Regulations and codes of practice offer generally accepted levels of safety for new construction, but flexibility is needed when dealing with old buildings. In '*Appraisal of Existing Structures*', the Institution of Structural Engineers recommends that 'when assessing existing structures, engineering judgement should take precedence over compliance with the detailed clauses of Codes of Practice for structural design' (IStructE, 1996). Similar guidance is also given by the British Standards Institution in BS 7913: 1988 '*Guide to the principles of the conservation of historic buildings*'.

Codes of practice for the design of new structures in timber and masonry may prove adaptable for use when assessing those materials in an existing structure. Good general guidance is provided in CIRIA Report 111, '*Structural renovation of traditional buildings*' (CIRIA 1986) and, by Poul Beckmann, in 'Structural *aspects of building conservation*' (Beckman, 1994). For more specific guidance on iron structures, reference should be made to Steel Construction Institute Publication 138, '*Appraisal of Existing Iron and Steel Structures*' (Bussell, 1997).

Buildings are most vulnerable to structural failure when in an incomplete state, either during construction, during structural alterations or after suffering severe damage caused by, for example, a fire or a gas explosion. Refurbishment, repair, and reconstruction works must be carefully planned, within the context of a well thought out Conservation Plan (see Section 1.5). Properly designed and constructed temporary works must ensure that the building or structure remains stable at all stages through to completion.

A holistic approach should be adopted when assessing a building. The first step is to try and understand how the structure supports its own weight, the loads imposed by its users, and wind forces. This involves tracing the paths taken by forces from where loads are applied, through the structure and into the foundations. In modern building frames, members and their connections are designed to carry forces (determined by structural analysis) along primary load paths that avoid 'non-structural' elements. The principles are covered very well in the Institution of Structural Engineers '*Stability of Buildings*' (IStructE, 1988). In existing buildings, load paths do not respect the assumptions of a structural analysis and the classification of elements as non-structural is generally difficult, or misleading. Glazing or cladding may act as wind bracing, for example. Aspects of the 'whole structure behaviour' of iron framed buildings are discussed in Section 7.

A stable structure is insensitive to minor disturbance. Stability is not a function of the strength of the elements of a building, but depends on how they are connected together and on how they interact with each other when the building is loaded. A robust building is stable but is also able to withstand an accident without the extent and severity of the resulting damage being out of proportion to its cause. When an existing iron-framed building of five storeys or more is subject to a change of use, compliance with the requirements for resistance to disproportionate collapse contained in Building (Scotland) Regulations may need to be demonstrated. Proposals under discussion at the time of writing may extend requirements for resistance to

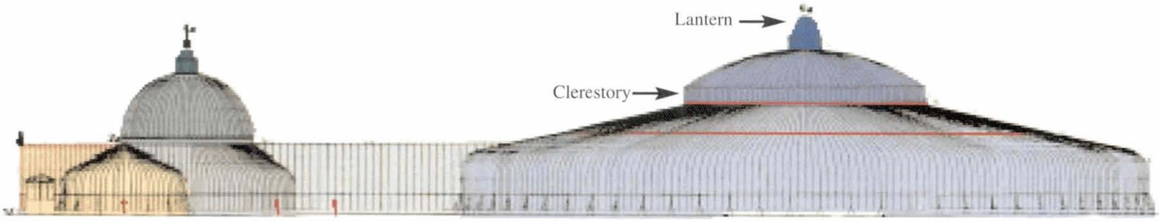


Illustration 143 The Kibble Palace, Glasgow Botanic Gardens (1873) side elevation (Picture: Glasgow City Council)

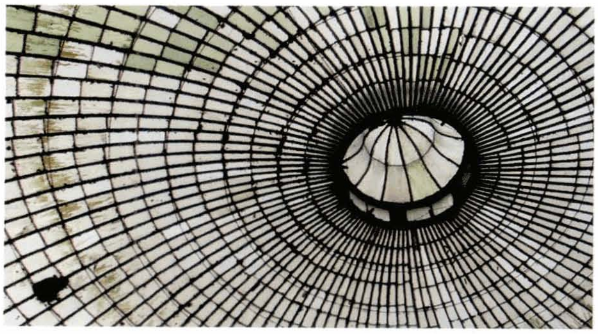


Illustration 144 The Kibble Palace, Glasgow Botanic Gardens (1873) (Picture: Glasgow City Council)
The rotational twist of the dome between the inserted clerestory and the lantern is apparent from the curvature of the glazing bars.

disproportionate collapse to most types of building, not just tall ones. Some guidance on improving resistance to disproportionate collapse is given in an Institution of Civil Engineers Design and Practice Guide '*Structural appraisal of iron-framed textile mills*' (Swailes, 1998) (see also Section 7.3).

As well as being safe, a building must also be fit for its purpose, or serviceable. Serviceability failures include excessive deflections or vibrations under load, unsightly cracking, or poor resistance to water penetration. Early in its life an old building may have deformed, perharps severely, into a state of equilibrium, and sometimes it will be both structurally and aesthetically desirable to leave it that way (Illustrations 143 and 144).

Cast iron is not a ductile material, but iron-framed buildings can generally withstand the effects of differential foundation settlement due to their relatively flexible beam to column connections. Some common and some less common forms of connections are illustrated elsewhere in this guide. Where connection details are inflexible or distortions are very large, the beams may fracture near their ends. Signs of settlement during construction can sometimes be seen by careful examination of the masonry elevations of many older buildings.

4.4 The effects of past structural alterations

Alterations may have been made to rectify defects, to modify a building for the changing needs of its occupants, or to adapt it for a new use altogether. Few buildings survive entirely in their original state and unravelling their history based on information that is rarely complete is a rewarding and, at times, frustrating experience. Many of the buildings covered by this guide are more or less dilapidated and have been modified several times. Part of a structural appraisal will be to identify past alterations, so far as this is possible, and assess their structural significance.

A structural appraisal is often part of a broader assessment of the suitability of a redundant building for a new use. This may result in a change in floor imposed loads. 'Non-structural' modifications may have structural implications. For example, if 'deafening' is removed from within a suspended floor to reduce its self-weight, the natural frequency of vibration of the floor may be changed for the worse. The floor may 'bounce' more when walked on and also be less effective as a barrier to sound.

Alterations may have involved moving a complete building to a new site. An iron-framed conservatory is a kit of prefabricated parts that are wedged, pinned, riveted or bolted together. Many such structures have been dismantled and re-erected using a combination of original and new parts, sometimes not with complete success. A nineteenth century example was built in 1865 by John Kibble as a conservatory at his house beside Loch Long. By 1873 the structure had been taken down and re-erected, much modified, in Glasgow's Botanic Gardens (Illustration 143).

It may be useful and it is always interesting to try and understand why a particular building has been modified. Sometimes modifications may have been made to correct an inadequacy or deficiency in the original structure. Buildings which contained industrial processes are quite likely to have been altered in the nineteenth or early twentieth century to accommodate changes in the size and weight of machinery, changes in power systems, changes in access and goods handling provision, or perhaps a change from production to storage. Only in a very few cases do buildings retain much early machinery or remnants of

Illustration 145 Dangerfield Mill, Hawick (1874) (Picture: T. Swailes) Original spinning mules by Platt Bros. of Oldham, and original drive shaft destroyed by fire in 2004

their original power transmission arrangements (Illustrations 145 and 146). Preservation of these rare in-situ survivals is of considerable historical importance.

Dramatic changes may have been made to the internal arrangement of a multi-storey building, without much consideration being given to the effect on overall structural stability. In some cases the first floor has been removed resulting in a double height lower storey (Illustrations 147 to 149). Vertical supports may similarly have been either moved or removed. The width between columns in the early fireproof mill buildings was limited due to the use of relatively primitive forms of cast iron beam. Nineteenth century engineers like William Fairbairn showed considerable ingenuity in adapting older buildings to accommodate new and larger machinery (Illustration 150). Historical research may provide plausible explanations for unusual constructional features (Illustrations 151 to 153). Sometimes alterations or additions may appear to be corrections of a poor original design concept (Illustration 154).

4.5 Structural assessment

4.5.1 General principles

The conclusions reached in the structural appraisal of a building will depend on the opinion of the engineer, based on his or her personal experience, informed to a greater or lesser extent by structural calculations. For old buildings, appraisal will generally be informed to a lesser extent by calculations, the main evidence being provided by the building itself. Signs of past structural movement are not always evidence of present distress. Careful medium-term monitoring of cracks or distortions may indicate a building is stable and that apparent defects date from a period early in its

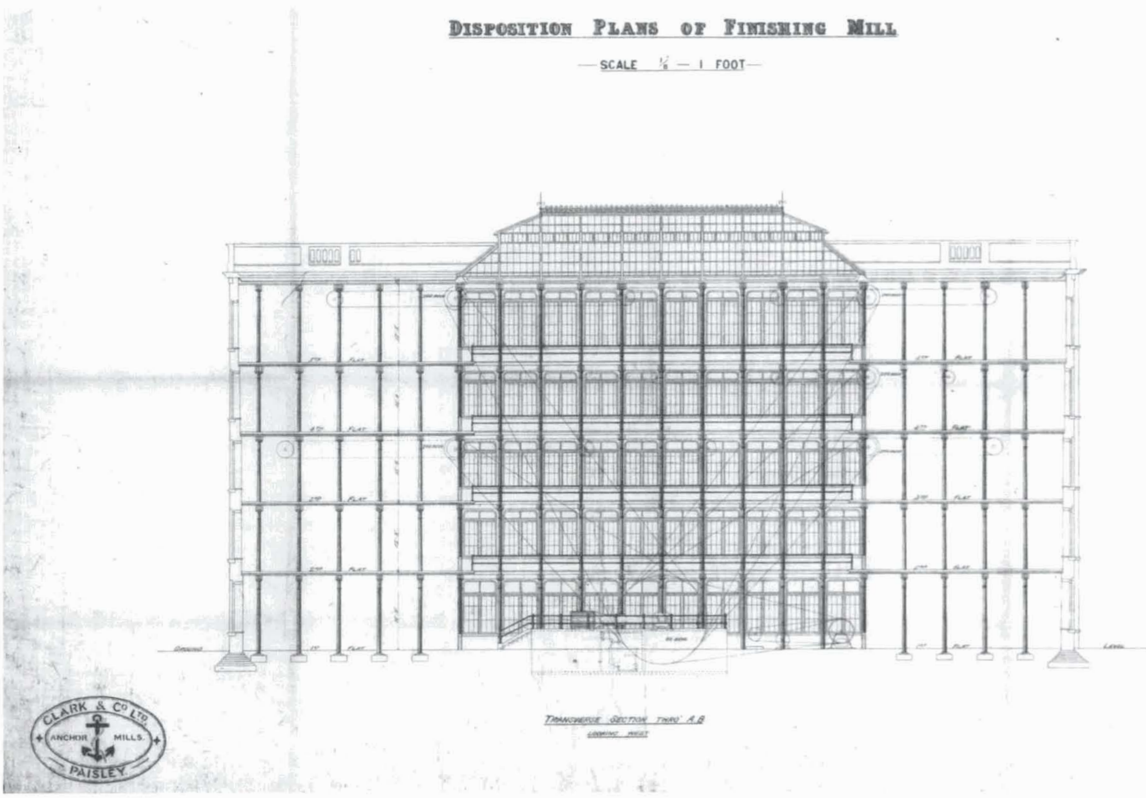


Illustration 146 Anchor Mills, Paisley: Domestic Finishing Mill (1889) Section showing the original rope drive arrangements (Picture: © Crown copyright RCAHMS Public Services)

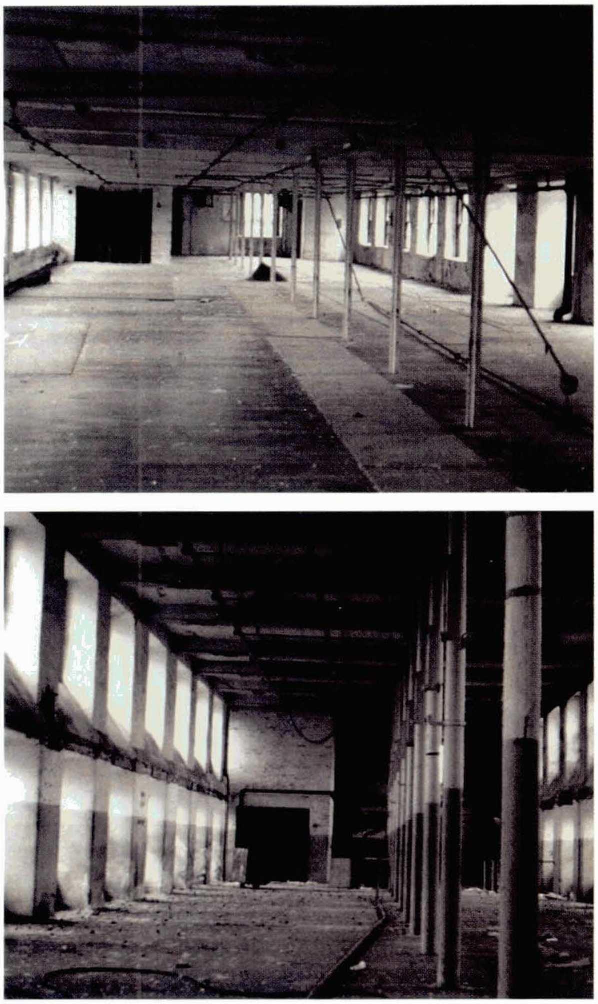


Illustration 147 (a) and (b) Bell Mill (or West Mill), Stanley Mills, Perthshire (1786-7)
(top) an original floor and (bottom) double height ground floor created by the removal of the original first floor.
(See Illustration 28 for the original storey post details)
(Pictures: T. Swailes)

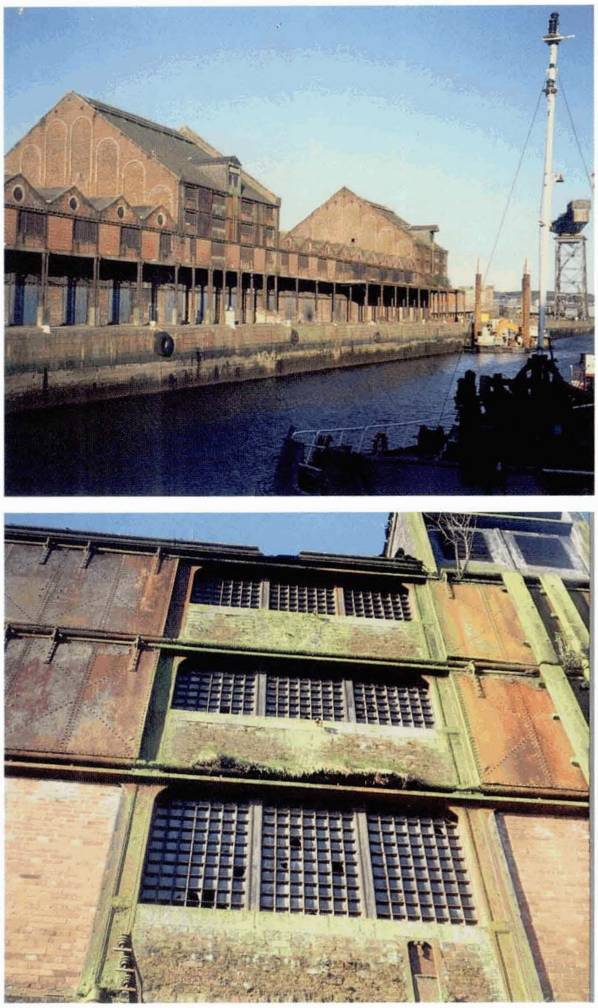


Illustration 148 Warehouse, James Watt Dock, Greenock (1885)
(a) General view (b) Detail of elevation to dock
Many elements of the iron frame have cast in part numbers presumably related to assembly drawings.
(Pictures: Mark Watson, Historic Scotland)

life, perhaps the result of initial settlement of the foundations. Imperfections are part of the character of an old building and worthy of conservation. Engineers need to develop a 'feel' for dealing with old structures in a sympathetic way and should avoid any temptation to meddle with a building that has stood the test of time. It has been suggested that rather than spend a lot of time calculating the structural capacity of an old building, scarce resources are better spent in examining the building and understanding why it stands up happily without modern intervention. Drastic interventions should not be contemplated before a building is well understood.

Where calculations are made, they will generally include a structural analysis to determine the effects of estimated loads on an idealised mathematical model of the structure. However, as noted in Section 4.3, the structural analysis of old buildings is problematic. The forces on structural elements and their connections obtained from the structural analysis are then used in stress analyses, also based on mathematical models, to determine the stresses in the materials for comparison with safe limiting stresses.

For convenience in the design of modern buildings, it is not unusual for the same factor of safety to be used for the assessment of all elements. This is an illogical approach that is difficult to justify for the assessment of existing structures. The failure of a column that extends over several storeys and supports many beams would have potentially more severe consequences than the failure of one of the beams. In a filler joist floor, transverse distribution of load may be able to compensate for a local weakness, so filler joists might be assessed using a lower factor of safety than isolated beams.

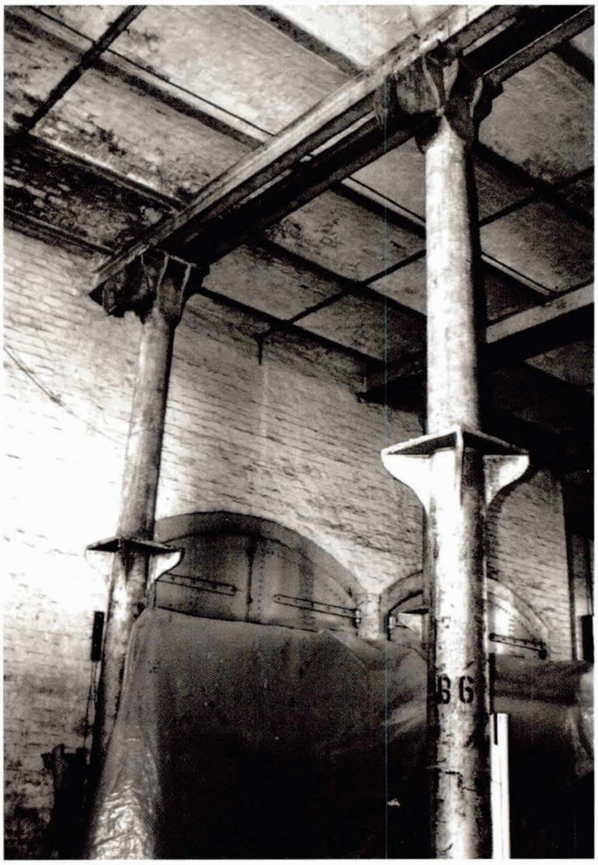


Illustration 149 Warehouse, James Watt Dock, Greenock (1885) Internal view showing intermediate floor removed (Picture: T. Swailes)

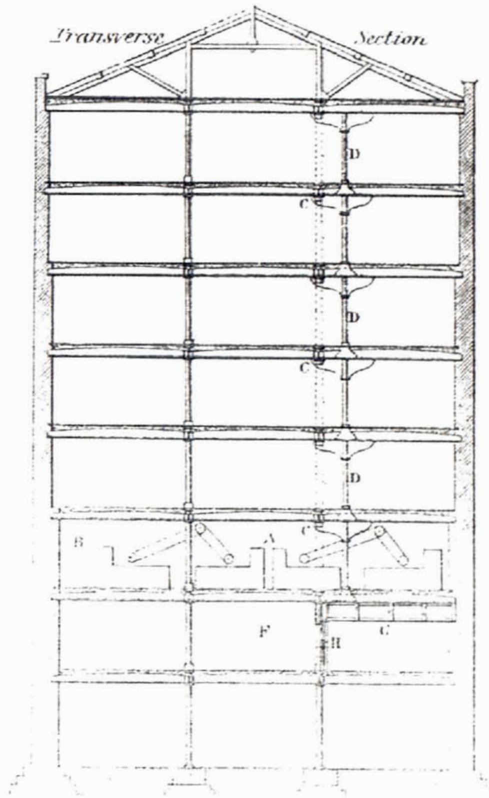


Illustration 150 Alterations to a Manchester cotton mill. Fairbairn devised a scheme that enabled a row of columns to be displaced laterally over the upper six storeys of an eight storey building, without stopping production. He introduced a wrought iron plate girder to transfer the concentrated load from the lowest of the offset columns (Fairbairn, 1866).

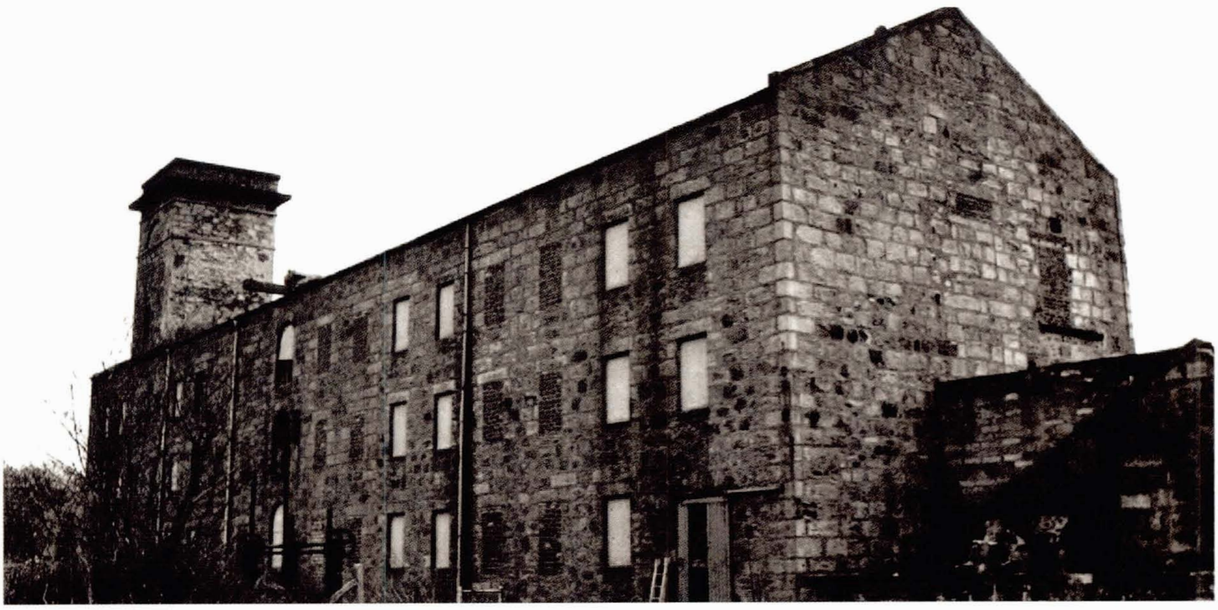


Illustration 151 The Old Spinning Mill, Grandholm Works, Aberdeen (c. 1790, modified 1820s and c. 1900) : Occupied from 1858-1991 by J&J Crombie, famous for tweeds and the Crombie coat, a flax spinning mill was here in 1793. Historical research has revealed that after a fire in 1900 the building, except the water/stair tower, was reduced in height by two storeys. (Watson, 1992) (Picture: T. Swailes)

Illustration 152 The Old Spinning Mill, Grandholm Works, Aberdeen (c. 1790, modified 1820s and c. 1900) Interior view (Picture: T. Swailes)

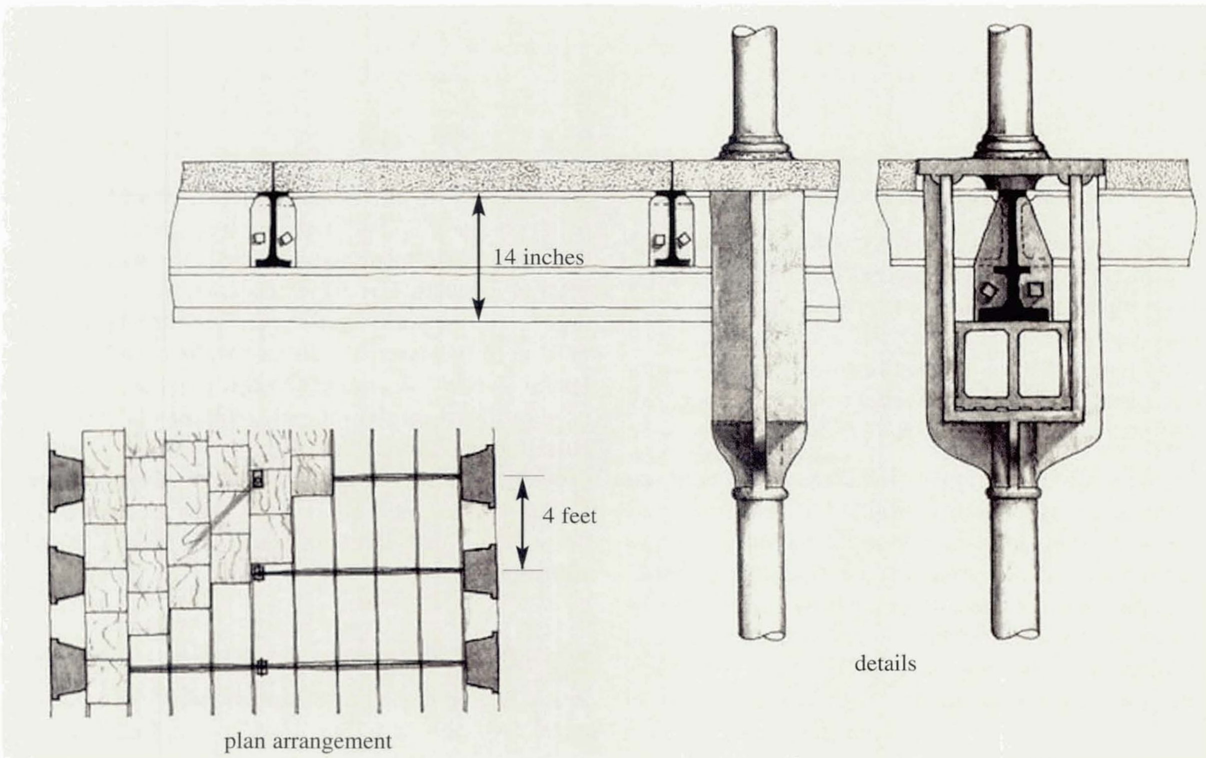


Illustration 153 The Old Spinning Mill, Grandholm Works, Aberdeen (c. 1790, modified 1820s and c. 1900) Details of cast iron-framed fireproof construction. Plans of 1821 indicate that the mill had timber floors. Fireproof additions to the works built in 1812, 1822 and 1826 have not survived. However, it seems likely that in the 1820s the upper floors of the old mill were replaced with the present fireproof construction of Caithness sandstone flags on a grid of cast iron joists and cast iron beams. An increase in headroom was achieved by supporting the cast iron joists within the depth of the main beams. Evidence of the original floor construction remains to parts of the ground floor over the basement (Picture: T. Swailes)

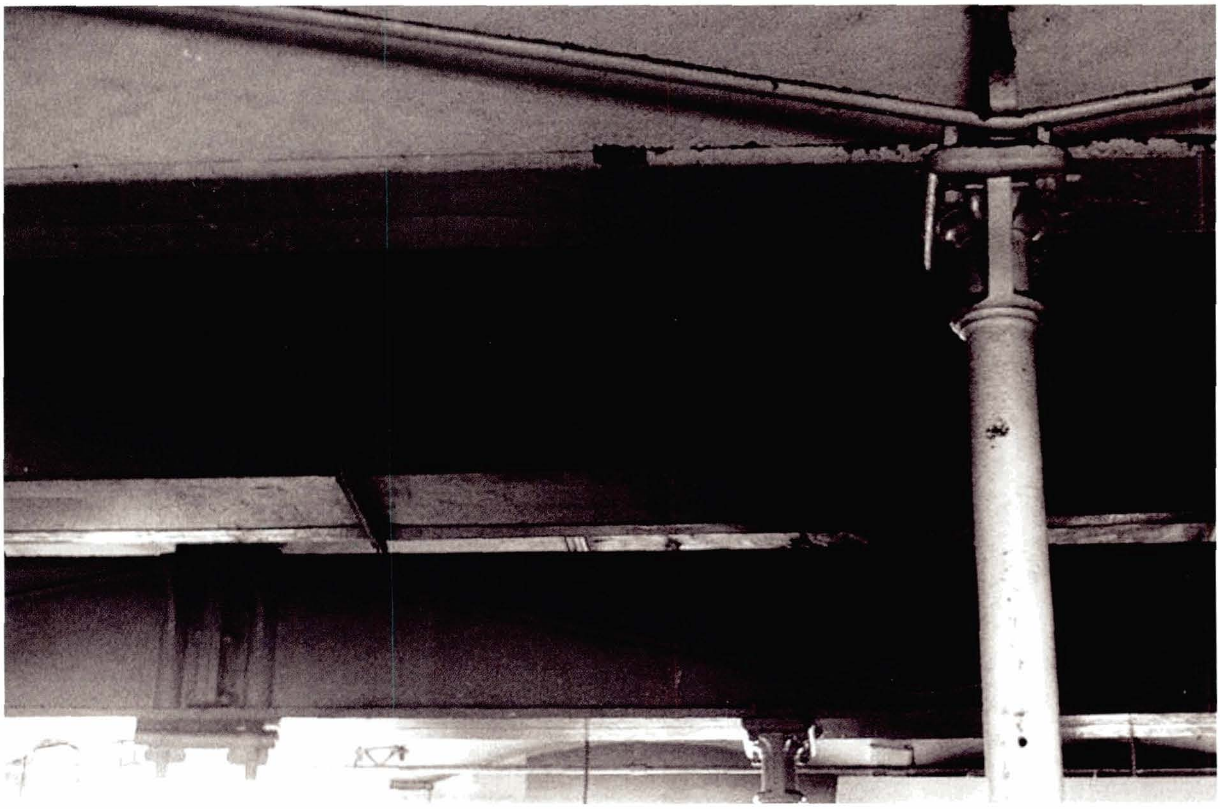


Illustration 154 Seafield Works, Dundee (1861) The multi-storey jute mill was converted to flats in 1988-1992, and contains examples of trussed cast iron beams that are propped between their original support positions by cast iron columns. External trussing of beams of timber or cast iron with wrought iron rods was tried in buildings from the 1820s in order to achieve longer spans, such as might be required locally over boilers or an engine house, The failure of one such example was reported to a meeting of the Institution of Civil Engineers (Fairbairn, 1847) (Picture: Mark Watson, Historic Scotland)

4.5.2. Stages in a structural assessment

Structural adequacy may be apparent in a 'first stage assessment', without resort to calculations, or by using very simple calculations. Such calculations will use a conservative analysis model and conservative, lower-bound material stress limits. Testing of materials may be needed to distinguish wrought iron from steel, for example.

If a building fails a simple first stage assessment, the initial analysis model is refined to more closely represent the actual condition of the building, in terms of member end and support conditions for example. Perhaps a three-dimensional analysis model will be created or allowance made for the inelastic nature of the materials. The removal of pieces of cast or wrought iron for mechanical testing with the sole aim of obtaining a higher safe limiting stress is not recommended (see Section 5). Steel, on the other hand, is a more consistent material and sampling and testing may be worthwhile.

A second stage assessment may involve site tests to validate a more accurate structural analysis model. Such tests will provide information about structural behaviour within the working load range, although they will not necessarily be reliable indicators of ultimate strength. For example, cast-iron framed textile mills were generally constructed with the beams well built in to the external masonry walls to help provide lateral stability. A simple site test procedure has been used to investigate beam end conditions in such cases (Illustration 155). When there is no floor above to provide a reaction, a temporary platform may be built to support weights for a load test, in the manner normally adopted for proof-loading of foundation piles (Illustration 156).

4.5.3 Static load tests

Proof testing involves the application of a load in excess of the working load to confirm that the performance of the structure will be satisfactory at working loads. It was common in the nineteenth century to prove components by testing. Many cast iron beams were proof-tested prior to installation (although the practice was not universal) and some iron

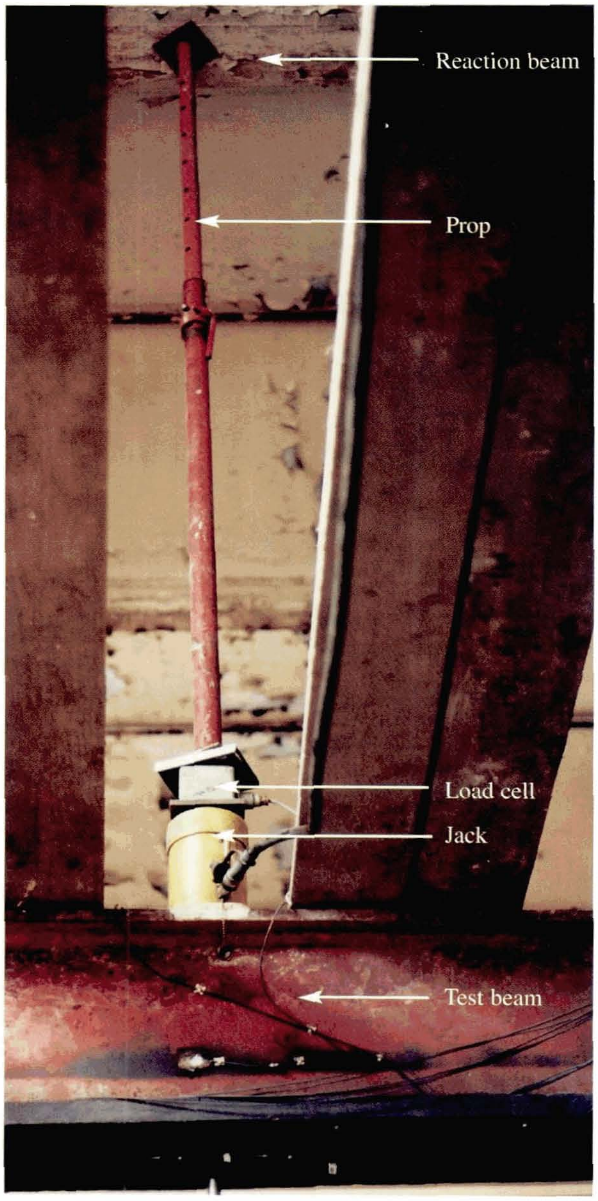


Illustration 155 Dean Clough Mills, Halifax, England: F Mill (1858)
In cast-iron framed textile mills, beam ends were usually built well in to the external masonry walls to help provide lateral stability. In a prop test, a concentrated load is applied at mid-span of the beam, via an adjustable prop placed on top of a hydraulic jack and load measuring device, with the reaction provided by the beam to the floor above (Swailes, 1995). Strain gauges are fitted along the soffit of the beam. Points of contra-flexure are determined from examination of the strain profile along the beam (Picture: T. Swailes)

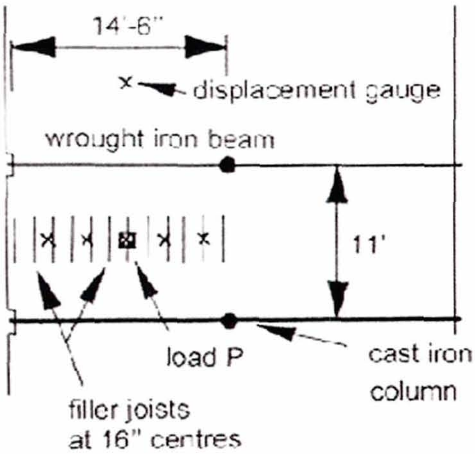
roofs were also proved by loading a truss or pair of trusses. Testing of a typical component does not 'prove' the remainder and, like the sampling and testing of materials, a quasi-statistical approach may be used in determining the number of tests to be carried out.

In existing buildings, proof-testing of floors, for example, can be an expensive and time-consuming procedure. However, a load test proving the adequacy of a structure that defies proof by calculation, but for which proof is required, is often less expensive than the unnecessary strengthening work that might otherwise be carried out. The Building Research Establishment recommended in IP9/89 '*Static load testing of building structures*', that: 'the test load may be chosen as the maximum the structure should sustain without suffering permanent deformation or damage, or (0.25 × dead load × 1.25 imposed load), whichever is less'.

Water is a convenient form of test load, as containers can be filled and emptied in a controlled manner. A nylon-reinforced rubber 'reservoir' was used successfully for instrumented tests on a floor in a modern building (Lloyd and Wright, 1992). Other papers on the load testing of modern buildings contain much information that may usefully be referred to when the testing of an iron-framed building is being contemplated (Menzies, 1978; Jones, 1978).

A satisfactory proof test will result in no structural damage, the response of the structure under the proof load will be nearly elastic, and the test will be repeatable. Isolation of a typical component under test is usually impractical and in testing a floor beam, for example, it is necessary to allow for the transverse distribution of load to adjacent beams by increasing the test load. Alternatively, all beams may be loaded. The stiffness of a floor may be increased greatly by composite action between the primary structural member under test and secondary members or finishes, but any corresponding increase in ultimate strength may be small.

Of course, there is a risk that a proof test will not achieve the desired result. A safety structure should be provided with the minimum possible clearance beneath the part of the building under test, to take the load in the event of failure. Adequate allowance must be made for dynamic loading effects. Back-propping through several storeys may be needed to prevent progressive collapse. In iron-framed buildings, it is necessary to consider the possibility of lateral instability and horizontal forces that may arise from the sudden failure of a bearing or connection or the brittle fracture of a cast iron beam. Fail-safe measures may include the provision of 'loose' vertical props and horizontal ties.



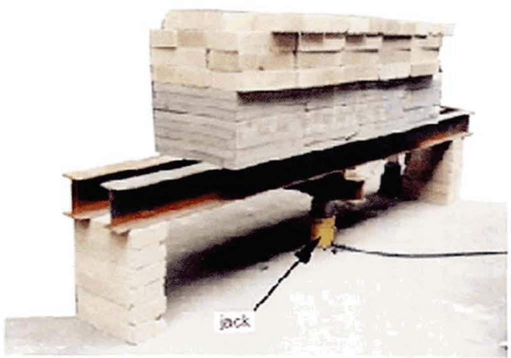


Illustration 156 Ashton-under-Lyne Library, Weights on a temporary platform providing a reaction for a localised test load on a filler joist floor. (Picture: T. Swailes)

4.5.4 Dynamic testing

Most buildings and bridges (except for suspension bridges) are essentially static structures and dynamic analysis is not used in their assessment. Even wind loads are reduced to equivalent static loads. However, dynamic testing may be used as a diagnostic tool by measuring either the ambient dynamic response of a structure or its response to forced vibrations. It is most useful in the assessment of 'pure' structures, in which interpretation of the dynamic response is not made difficult by the stiffening effects of 'non-structural' elements. Potentially at least, it is a technique by which data can be obtained for more realistic computer modelling and analysis of structures. One application has been a comparative investigation of the condition of a series of nominally identical stone pinnacles to the Houses of Parliament in London (Ellis, 1998).

5 MATERIAL PROPERTIES

"To the student in architecture, engineering and building, there is scarcely any acquirement more essential to professional success than a knowledge of the properties of materials which are used in construction. It is more important than either skill in design or correctness of proportion, whatever the character of the structure – be it a house, a ship, a bridge, or a machine." (Fairbairn, 1852).

5.1 Introduction

The essential features of wrought iron and cast iron are described briefly in Section 1.3. Illustrations 5 to 8 show typical fracture surface textures and microstructures for the two materials.

The engineering properties of wrought and cast iron are considered in more detail in this section. Methods of manufacture and how they influence material properties are described. Some modern test results are summarised in tabular form to enable a quick comparison to be made between the mechanical properties of wrought iron, cast iron and early mild steel (Illustration 157).

The extent to which historical materials test data from the nineteenth century may be relied upon today is considered. The earliest tests on iron were carried out with very little scientific understanding of many of the factors that determine the properties of the material. Metallurgy was in its infancy at a time when the structural use of cast iron was in decline. Dr Percy, the pioneer of British metallurgy, first lectured on the subject at the Royal School of Mines in 1852.

5.2 Wrought iron

5.2.1 Metallurgy and texture

The best wrought iron would generally have carbon and silicon contents of less than 0.2%. With more carbon or silicon, the iron would be harder and less tough. The chemical composition of a bloom of iron found on the site of sixteenth century forges on the shores of Loch Maree in Wester Ross was as follows: Carbon 0.192%, Silicon 0.077%, Sulphur 0.02%, Phosphorous 0.087%, Manganese 0.038%. A piece cut from the bloom had a tensile strength of 25.4 tons/in^2 (392 N/mm^2), a yield stress of 13.6 tons/in^2 (210 N/mm^2), and an extension at failure of 10.5% in a length of 10" (Dougal, 1894).

Evidence of iron making on a 'domestic' scale in Scotland, sometimes in the form of nothing more than furnace slag or cinder, dates from the first century BC (Tylecote, 1986). For making knives or swords at this time, relatively high phosphorous iron would be suitable, harder material being better able to 'take an edge'. Iron with 0.5% phosphorous, cold hammered or cold worked to reduce the thickness of the piece by 10%, has been found to have a hardness of 300 HV. This is twice as hard as iron with 0.1% carbon, subjected to the same treatment. Such high phosphorous iron would be 'cold-short', or lacking ductility at normal temperatures, and would not be suitable for general blacksmith's work or structural applications. This helps to explain why the early Scottish ironworking industries relied to some extent on bar iron brought from Sweden and Russia, made from ores containing little phosphorous. Sulphur and copper were other impurities that, even in small quantities, would render the iron 'red short', or difficult to work when heated.

The appearance of the fracture of a wrought iron bar in tension depends to a considerable extent on the method of test and in particular on the rate of strain (Illustration 158). Wrought iron cools as it is rolled and the material crystallises to a solid. The crystals are not themselves elongated by the rolling process but they form instead in 'fibres' in the direction of rolling. Under impact loading, or at high rates of strain, failure will take place by cleavage of the crystals, exposing bright crystal facets in the fracture. At lower rates of strain, the crystals will separate along their edges, which show as a lustrous dark blue-grey colour in the fracture. It is common with wrought iron tensile test specimens to see bright crystalline clusters within a generally dark blue-grey fracture, showing variation of the material properties or stress distribution between individual 'fibres'.

In its finished state, wrought iron comprises thin layers of almost pure iron with thin threads of slag visible between, except in the very best iron. These layers or laminations, around 1mm to 3mm thick, may be apparent on inspection of the edges of a machined test piece. Sometimes, on pieces of wrought iron with quite severe surface corrosion, the grain or fibre of the material will be visible in the direction of rolling.

WROUGHT IRON

[1]**Bar** 30 × 30 square section	Tensile test results				
	0.2% proof stress N/mm²		ultimate stress N/mm²		*elongation* at failure %
	mean	range	mean	range	
	243	225 - 250	382	337 - 398	14 - 32

The bar acted as a nominal tie in the iron framing to a mid-nineteenth century textile mill. Test samples were cut from along the length. The irregular appearance of the fractures and a relatively low density showed the bar to be of poor quality iron.

Rolled Joists 202 × 86 I-section	Tensile test results							mean Charpy impact **Joules**	mean Hardness **HV 20**
	0.2% proof stress N/mm²		ultimate stress N/mm²		elongation at failure %	mean density kg/m³	mean E value kN/mm²		
	mean	range	mean	range					
[1](A) web									
flanges									
[2](B) web	343	325 - 355	460	421 - 478	7 - 14	7770			150
flanges	299	280 - 325	436	410 - 466	11 - 20	7800			
[3](C) web	244	-	374	-	18		195	23	185
flanges	267	262 - 271	371	358 - 384	5 - 12		194	10	161

Tests on samples from three nominally identical joists, A, B and C, from a c.1868 'Fox & Barrett' floor in the Royal Albert Hall. There is some circumstantial evidence that the joists were imported from Belgium.

EARLY MILD STEEL - for comparison

[2]**Beam** 304 × 150 I-section	Tensile test results							mean Charpy impact *Joules*	mean Hardness **HV 20**
	0.2% proof stress N/mm²		ultimate stress N/mm²		elongation at failure %	mean density kg/m³	mean E value kN/mm²		
	mean	range	mean	range					
web	*260*	*257 - 262*	*458*	*449 - 467*	*24 - 32*	*7840*	*197*	*40*	*141*
flanges	*228*	*221 - 232*	*449*	*447-450*	*28 - 33*	*7830*	*198*	*33*	*143*

Tests made on steel samples taken from a beam, dating from c.1905, and marked *'Frodingham Iron and Steel Company'.*

CAST IRON

	Av. Tension Flange Section Modulus, Z_t mm³ × 10⁵	Full-scale Bend Test Results		Small Bend Tests	Tensile Tests
		Modulus of Rupture, f_{bt} N/mm²		f_{bt} N/mm²	Tensile stress, f_t N/mm²
		mean	range		
[4]**Beam type 1**		99	91 - 113	207 - 253	121 - 132
[4]**Beam type 2**		117	99 - 134		
[5]**Beam type 3**	24.3	140	105 - 186		158 - 202
[5]**Beam type 4**	1.82	204	66 - 269		205

All beams dated from the mid-nineteenth century and were of flake graphite cast iron. Small bend tests were 12.5 × 25 rectangular bars cut from a beam of close to the average bending strength and tensile tests were generally on 16mm diameter specimens.

Sources of test data

[1] Kontos, N. 'Investigation of Wrought Iron as a Structural Material', MSc Dissertation, UMIST, 1996.
[2] Anastassopoulos, A. 'Structural Appraisal of old Iron Beams, MSc Dissertation, UMIST, 1997.
[3] Steude, T. 'The Strength of Wrought Iron and early Mild Steel Beams', MSc Dissertation, UMIST, 2000.
[4] Swailes, T. & Parmenter, M. 'Full-scale laboratory tests on cast-iron beams and an investigation of size effects', in Virdi, K S et al (Eds), 'Structural Assessment: the role of large scale and full-scale testing', E & F.N. Spon, 1997, p260-268.
[5] Swailes, T. & Marsh, J O. 'Structural Appraisal o f Iron-framed Textile Mills', ICE Design & Practice Guide, Thomas Telford, 1998, p51.

Illustration 157 Tensile and Bend Test Data for Nineteenth Century Structural Iron

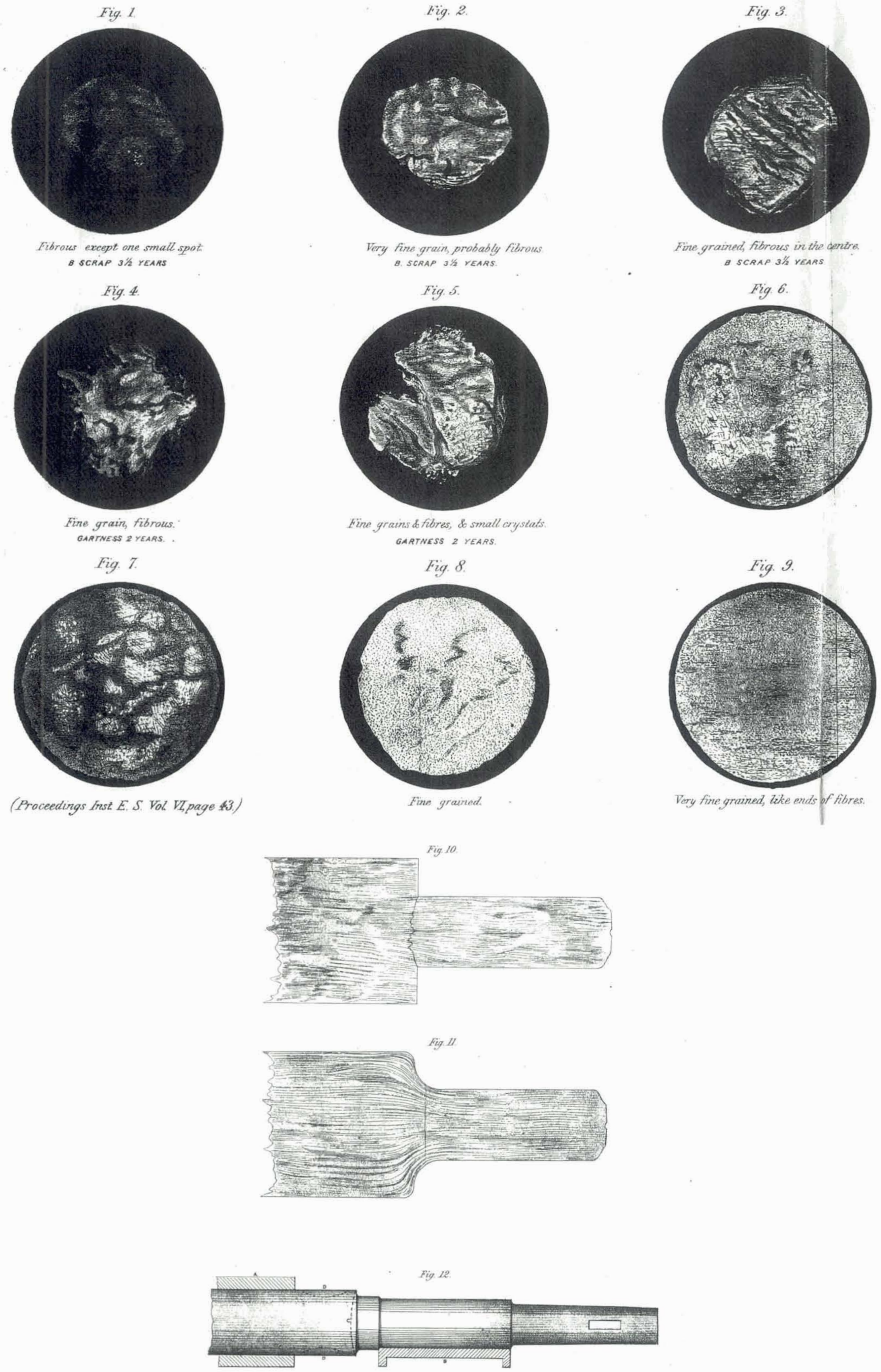


Illustration 158 Wrought iron axle fractures
Accidents on the early railways resulting from the fracture of wrought iron axles led to research to determine the cause of such failures. Tests on axles for the London & Birmingham Railway Company showed both crystalline and fibrous fractures under impact loading (McConnel, 1843). Tests elsewhere produced similar results (Thorneycroft, 1850). Contributing to the discussion of a paper by David Kirkaldy to the Institution of Engineers in Scotland, W.J.M. Rankine presented these details of axle fractures (Source: Rankine, 1863).

5.2.2 Manufacture

Practice in making 'industrial' wrought iron in the late eighteenth and nineteenth century varied, but repeated re-heating and re-working was always used to achieve a better end product. The first stage of the process, as described by Aitken in 1826, was as follows:

'The pigs, being broken into two or three pieces each, are remelted in the refinery furnace (with coke), and the produce being let out into a shallow, flat, cast-iron trough, forms thick plates, called slabs'.

The slabs (3 ½ cwt in total) being broken, are melted in the puddling furnace (with coal), and brought out in large masses, called balls; which while yet glowing hot, are laid under a very heavy hammer, and stamped into plates, which are then thrown into water, in order to cool them.

The plates, being broken, are piled one on the other, to the height of about a foot and a half, and placed in a reverberatory furnace, called a boiling furnace; from which, when sufficiently heated (by coal), they are removed to the shingling hammer, where they are beaten into short, thick bars, called blooms (2 ¾ cwt in total) (Aitkin, 1826).

The bloom was the starting point for the manufacture of higher quality iron by mechanical working, and re-heating a number of times (Illustrations 160 and 169). The product of the first rolling of the bloom was 'muck bar' or 'puddled bar', typically of 6" × 1" section (Gale, 1965). This was cut up cold, several pieces were then stacked or piled, reheated and welded into a solid mass by hammering, then rolled to produce 'common', 'merchant' or 'crown' iron (Illustrations 161 and 162). A second re-rolling produced 'best' iron (The British Standard Grade B was a later equivalent), for general structural work. A third re-rolling produced 'best best' or 'BB' iron (equivalent to the BS Grade A), for rivets and chains (Morgan, 1999). 'Best-Yorkshire' was a description reserved for iron of the highest possible quality (Skelton, 1924).

The piling of rectangular section bars of iron for re-heating and re-rolling took several forms. In the 'plate pile', for finished products such as chain links that were to be stressed longitudinally, the cut bars were piled with their axes parallel to the direction of stress. A variant was the 'box pile', with a piece of iron placed on edge either side of the plate pile, to box it in. Cross piling was used for boiler plate, subject to bi-axial stress, with the cut bars arranged in alternate layers at right angles.

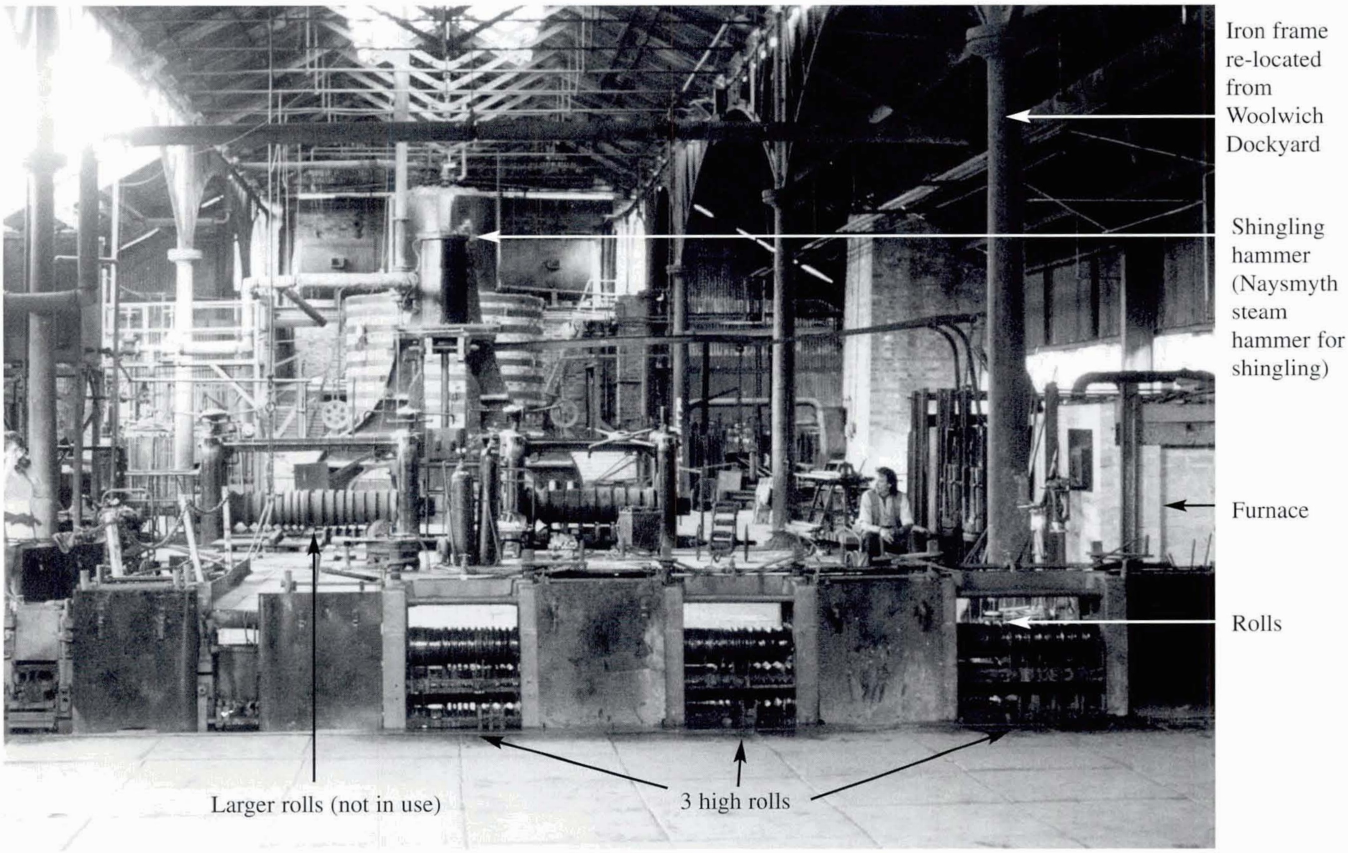
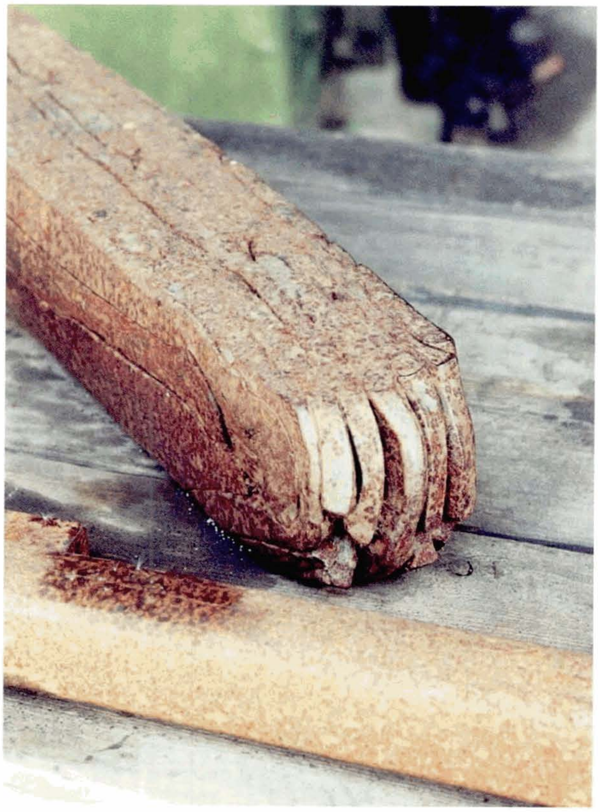


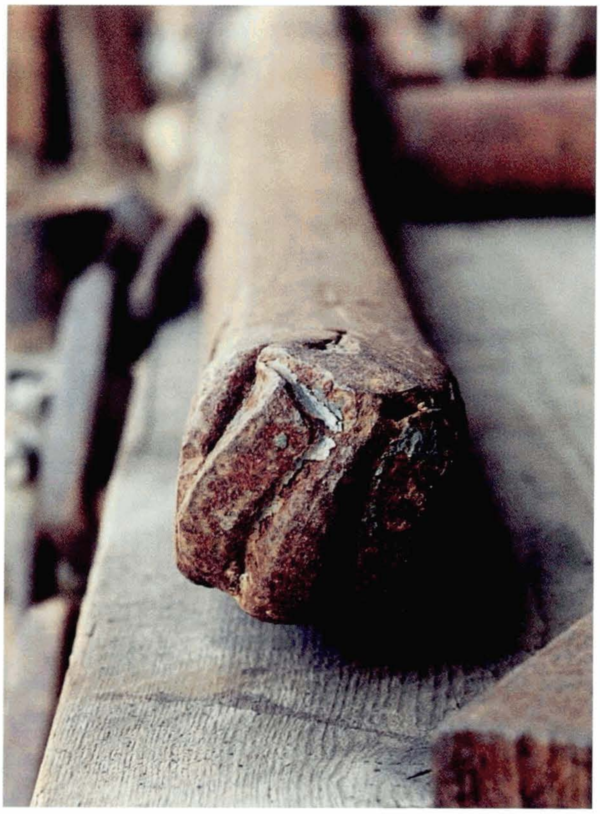
Illustration 159 The Ironworks at Blist's Hill, Ironbridge (Picture: T. Swailes)
A small set of rolls is in the foreground. In the background are a larger set of rolls and a shingling hammer

a. Piled bars, each 240mm x 70mm x 12mm

b. Shingled pile (welded under the hammer)



c. Shingled again, much distorted under the hammer



d. Rough rolled bar 50mm square

Illustration 160 Wrought iron samples at Blist's Hill, Ironbridge (Picture: T. Swailes)

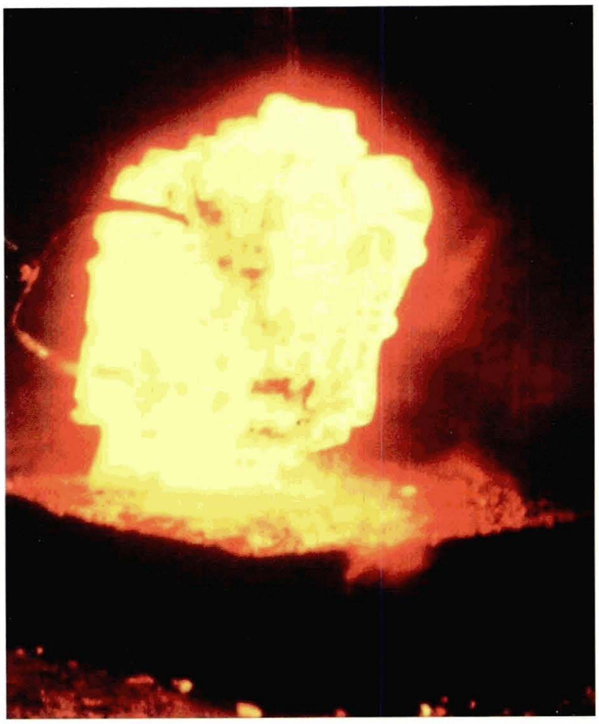


Illustration 161 Iron ready for working under the steam hammer (Source: Minter, 1990)

Early in the nineteenth century, iron was worked under a water or steam powered forge or tilt hammer. In 1839 James Nasmyth invented the steam hammer, which from the 1840s was an absolutely indispensable ironworking tool (Illustration 163). The steam hammer was far superior to anything previously available for 'shingling' wrought iron, preparatory to rolling.

5.2.3 *Mechanical properties*

(a) Tensile and compressive strength

Stresses for wrought iron for use in a structural assessment, using either permissible stress or limit states principles, are reviewed in a recent Steel Construction Institute publication (Bussell, 1997). BD21, the standard for the assessment of highway bridges and structures, gives characteristic yield stresses of 220 N/mm^2 for wrought iron and 230 N/mm^2 for early mild steel. The established procedures for the assessment of early mild steel in structures can generally be adapted for the assessment of wrought iron. The differences between the two materials are considered in this sub-section, with some typical test data provided for comparison purposes.

Yield stresses obtained in recent tests on wrought iron and early mild steel are given in Illustration 157. For samples from the rolled wrought iron joists, the

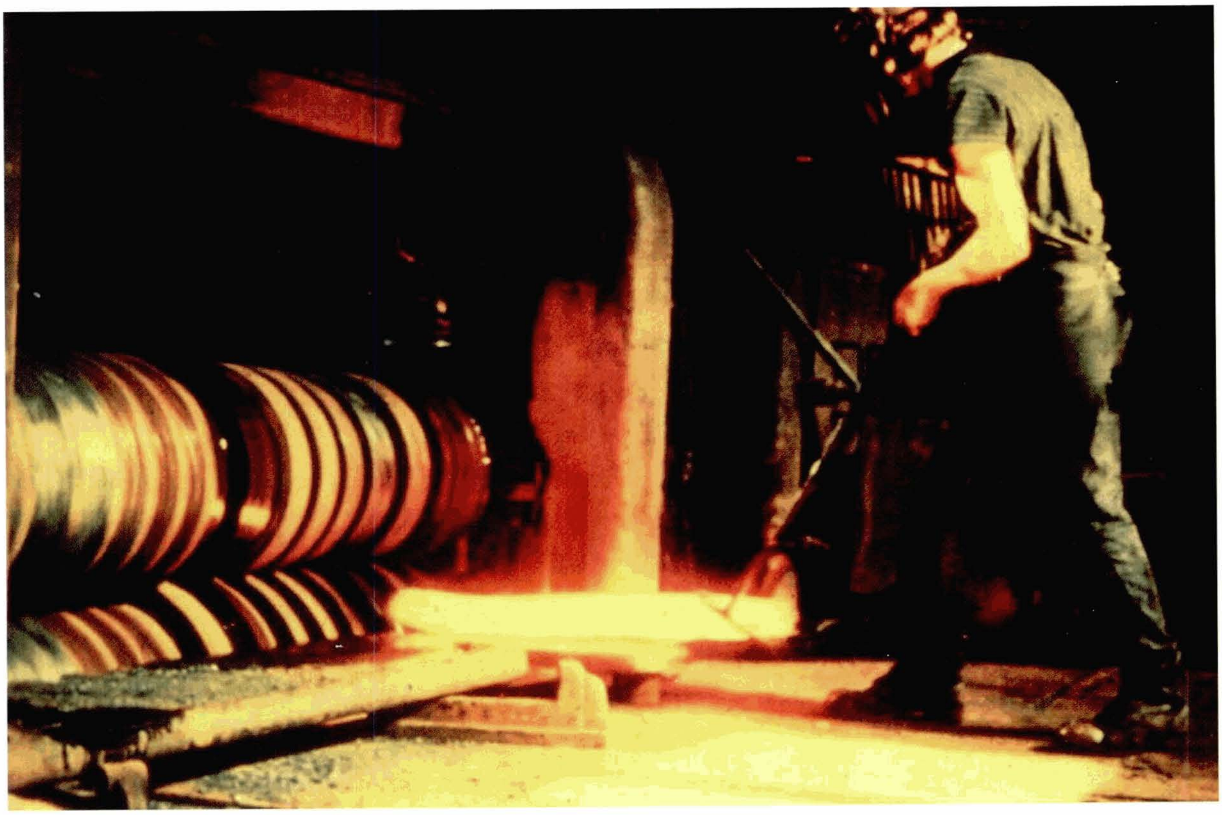


Illustration 162 Passing a heated iron bar through the rolls (Source: Minter, 1990)

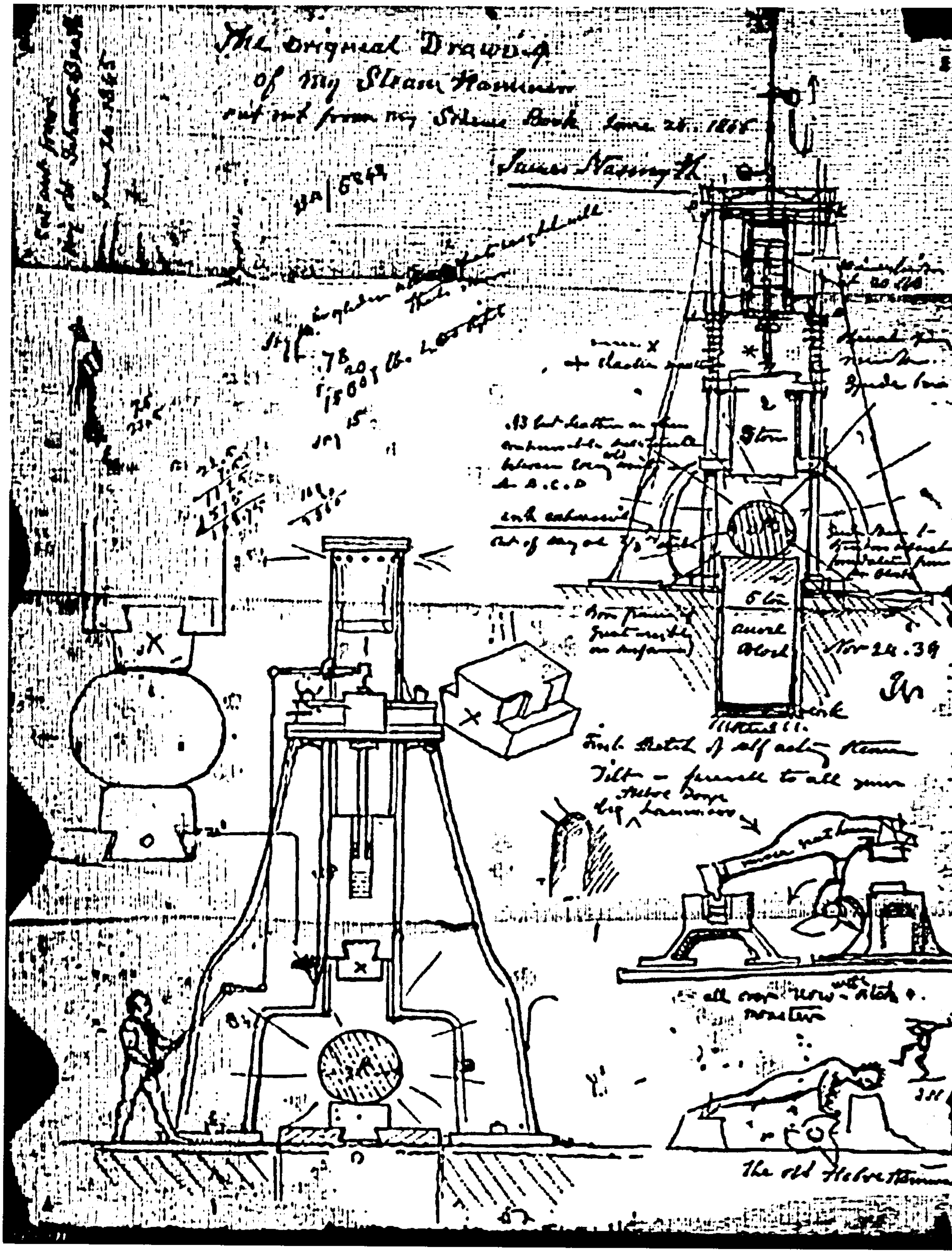


Illustration 163 James Nasmyth's original sketch for the steam hammer
The traditional forge or tilt hammer, whether powered by water or steam, was most suitable for small forgings as a larger piece placed on the anvil would take up the space needed for the fall of the hammer. In a typical early steam hammer, a massive five ton hammer block was attached to the piston rod of an inverted steam cylinder, arranged so as to be able to fall by gravity 5 feet or more onto the work piece on the anvil. In later hammers, the fall of the hammer was assisted by steam pressure acting from above (Source: from James Nasmyth, engineer an Autobiography edited by Samuel Smiles London, John Murray, 1897.

ultimate stresses are close to those for the mild steel beam samples, but the yield stresses are much higher. Some cold working during the rolling of the joists probably raised the yield stress (known as the 'Bauschinger effect', after its nineteenth century discoverer). The use of a 'characteristic' yield stress for wrought iron in excess of 220 N/mm² is not recommended, and the analysis of test data may well lead to the adoption of a lower value. Wrought iron is a less consistent material than early mild steel, with greater variation in properties between structural sections and within a single section.

(b) Toughness

The Charpy values in Illustration 157 obtained at room temperature for samples from the early mild steel beam are close to the minimum expected for a modern low carbon steel (carbon content < 0.25%). On the other hand, the Charpy values for the wrought iron joist samples are much lower and their ductility, measured in terms of percentage elongation at failure, is poor. These rolled iron joists have strength, but at the expense of toughness and ductility. Toughness tests showed the wrought iron from S.S. Great Britain to be even worse. The energy required to break notched impact specimens of wrought iron from Brunel's ship at 20°C was about 4 ft.lb (5.4 Joules), a tenth of that obtained for specimens of a modern mild steel (Morgan, 1996). At the other extreme, Charpy values for wrought iron tie bar material from an 1887 trussed bridge in the U.S.A. ranged from 34 Joules to 144 Joules (Badoux, 1998). Wrought iron of so many qualities exists that no assumptions can be made about toughness. Some material is very poor and some very good, but one kind can only be distinguished from the other by testing.

(c) Directional properties

The strength of wrought iron plate, made by the cross piling of bars prior to rolling, is typically about 85% of the strength of wrought iron bars rolled from the same material (Kirkaldy, 1863). The strength of a plate tested 'in the direction of the grain' (presumably the direction of the outer bars in a cross pile) was reckoned to be about 10% greater than that across the grain (Box, 1883). The influence of direction on properties may provide an explanation for variations in results obtained when testing samples of wrought iron during the course of a structural assessment. With respect to toughness, one authority quotes tests on a wrought iron giving an 'impact value' in the direction of rolling of 17.5 ft.lb (24 Joules), compared with 4.8 ft.lb. (6.5 Joules) perpendicular to the direction of rolling (Salmon, 1931).

5.2.4 Temperature and cold-working effects

In the nineteenth century and early twentieth century, a number of quick quality tests were used in the blacksmith's shop to confirm the cold and hot-working characteristics of iron (Illustrations 164 to 166). Such tests might be the norm for wrought iron for railway structures but were probably not specified for most iron used in buildings.

Punching of holes was preferred to drilling by structural ironwork fabricators, being a quicker and cheaper process. In the absence of subsequent heat treatment, punching would cold work the iron around the hole, leaving it locally harder and more brittle. In tests on boiler plate from several Yorkshire ironworks, it was found that punching holes reduced the static strength of a wrought iron plate by around 15% (Box, 1883). The problem was more severe in early steels. Barba found that the material within 1/8" of a sheared edge or punched hole in steel plate became very strong, hard and brittle (Unwin, 1910). One solution was to punch 1/8" undersize and then ream the hole to the required diameter, thus removing the cold-worked material. Some attempts in the 1860s to use relatively hard 'puddled' steel for structural purposes failed because the effects of fabrication processes on the material were not understood.

An illustration of the detrimental effects of cold working and the effectiveness of annealing as a remedy were provided by James Nasmyth. Three experiments were made on 'a bar of the very best 1 3/4" square wrought iron', prepared in different ways, then laid over an anvil and struck with a heavy hammer (Illustration 166). Nasmyth's tests showed the necessity of annealing wrought iron mechanical engineering components that were to some degree cold worked during manufacture, such as railway axles. Subsequent more scientific investigations showed that annealing led to a slight reduction in static tensile strength but a slight increase in ductility.

Steels in the medium carbon (> 0.25%C) and high carbon (> 0.5%C) categories are made hard and brittle when heated to the correct temperature and then cooled rapidly. Reheating to a lower temperature followed by cooling tempers the steel, 'letting down' the hardness and restoring a degree of toughness. Wrought iron, like mild steel, is not susceptible to heat treatment in this way. On cooling after exposure to high temperatures in a building fire, the strength properties of wrought iron will be unaffected. In fact, some gain in strength properties after exposure to high temperatures was found in tests on a late nineteenth century wrought iron with a relatively high phosphorous content of 0.25% (Kirby, 1986). During a fire, the structural behaviour of wrought iron is very similar to steel, the yield stress falling to about half its initial value at about 500°C. Where moderate distortion of wrought iron elements

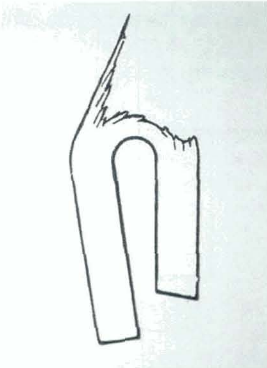


Illustration 164a 'A bar is nicked and then bent (slowly), the fibrous or non-fibrous nature of the specimen being exhibited at the fracture. For good wrought iron the fracture should show a silky fibre'. A bar nicked and bent in this manner is shown in Illustration 5

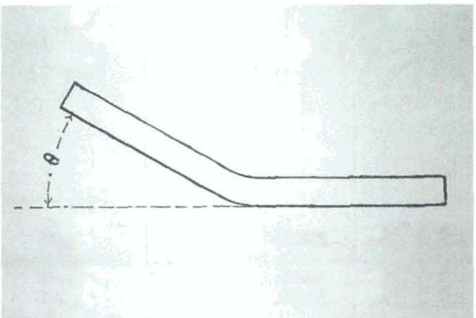


Illustration 164b Admiralty tests for wrought iron plate specified minimum angles to which plates of different thicknesses should be able to be bent when cold without fracture (Popplewell, 1901)

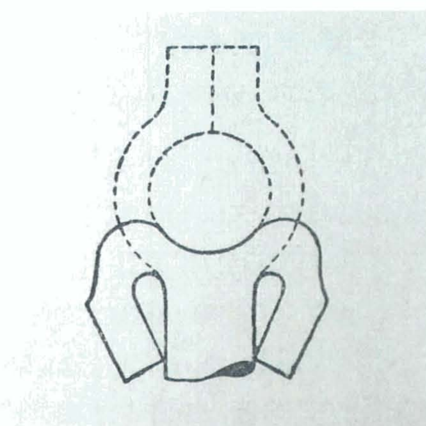


Illustration 164c A bar specimen is punched at a full red heat (1500 to 1600°F) with a punch 1/3 the diameter or width of the bar, at a distance from the end of the bar of 1½ times the diameter or width. The end of the bar is then split up to the hole, and then the two halves turned back. The test is failed if the original split extends or other indications of fracture, cracks or flaws develop. This was one of the tests in the early twentieth century British Standard specification for Grade B bar iron 'for general purposes', the superior Grade A being reserved for chains, cables, etc. (Skelton, 1924)

Illustration 164 Nicking and cold bend tests for wrought iron

has occurred as a result of fire, it is at least theoretically possible to straighten them for reuse or recycling, with the proviso that the effects of possible cold working must be removed by annealing.

5.2.5 Forge welding

The earliest iron beams in Britain, dating from Roman times, were made by forge welding together small blooms of wrought iron. A 1.72m long 2nd century beam, found at Catterick, had cross section dimensions of 15 cm × 13 cm at the ends, 18 cm × 18 cm at mid-span, and a mass of c.250 kilogrammes (Tylecote, 1986). Such beams appear to have been used over bath house furnace stoke holes.

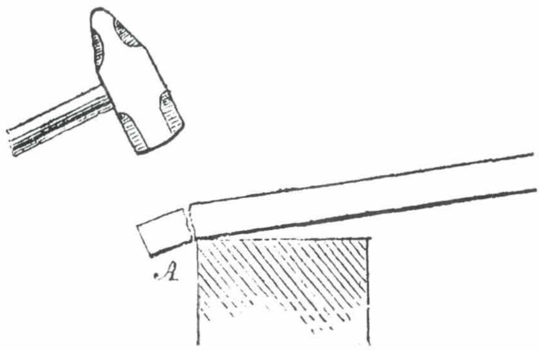
For the forge welding of wrought iron, Henry Adams advised that 'the pieces must be brought to a white heat and the scale swept off before they are put together' (Adams, 1907). David Kirkaldy carried out tensile tests in the nineteenth century on 18 forge welded wrought-iron bars from ¾" to 1¼" diameter, and obtained joint efficiencies from 56% to 97%, with a mean of 81%. The loss of strength due to welding of steel was found to be greater, with joint efficiencies from 40% to 55% (Box, 1883). With suitable equipment, and appropriate expertise and quality control, forge welding of wrought iron is still a practical proposition.

Prior to Nasmyth's invention of the steam hammer, large forgings such as ships anchors were made using what he called the 'bit by bit' system. Separately forged pieces were heated and welded together, but the welds were too often imperfect. By contrast, on the anvil block of the steam hammer, all parts were welded together into a homogeneous mass. Common iron was considered unsuitable for forging, as the scale or slag in it caused cracks. According to one authority, 'double best' and 'treble best' Staffordshire iron or ordinary Yorkshire iron were suitable for forgings, best Yorkshire being reserved for difficult work (Adams, 1907).

5.2.6 Historical test data and materials testing

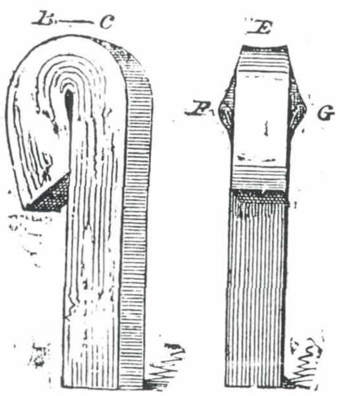
Some historical test data on wrought iron has been brought together by James Sutherland (Doran, 1992). Early test reports for wrought iron give breaking loads, but can not be relied on for the more important elastic limit or yield point. Hydraulic testing machines were in use from early in the nineteenth century as an alternative to loading via dead weights. The Admiralty testing machine at the Woolwich Dockyard was made by Bramah & Co. of Pimlico (Joseph Bramah being the inventor of the hydraulic press) for tests on cables and chains. The machine, with a frame length of over 100' and able to exert a pull in excess of 100 tons, is

Illustration 165 A variant on the Ram's Horn Test for wrought iron on display in the Royal Museum, Edinburgh (Picture: T. Swailes)



Test 1 The bar broke after 9 heavy blows of a large sledge hammer, 'exhibiting that clear crystalline texture due to a good quality of iron at that temperature'.

Test 2 (not illustrated) A piece of the same bar was raised to a red heat, then the surface of the bar was hammered until nearly cold. The bar broke after one slight blow from the hammer, showing a close crystalline fracture of the type obtained with steel.



Test 3 A piece of the same bar was raised to a red heat, then the surface of the bar was hammered until nearly cold. The bar broke after one slight blow from the hammer, showing a close crystalline fracture of the type obtained with steel.

Illustration 166 James Nasmyth's wrought iron bar tests (Source: Nasmyth, 1842)

described and illustrated in one of the earliest books devoted to the strength of materials (Barlow, 1837).

David Kirkaldy carried out an important series of tests on wrought iron and 'puddled steel' for Robert Napier & Sons of Glasgow. Interim results of the tests were published in the Transactions of the Institution of Engineers in Scotland in 1859, and the full results published later in a book, giving the ultimate strengths of a wide variety of wrought irons (Napier, 1859, and Kirkaldy, 1863). Kirkaldy's results were diseminated widely (Illustration 167). In discussions of the work at the Institution of Engineers in Scotland in late 1862, W J M Rankine advocated the use of the elastic limit or stress at yield, rather than stress at breaking, as the measure of strength. Soon afterwards, Kirkaldy established his famous materials testing laboratory at Southwark, now preserved as a museum (Smith, 1981).

In the last quarter of the nineteenth century, materials testing laboratories were set up in several technical colleges and universities. One of the most active was run by Alexander Kennedy, from 1874 Professor at University College, London. The testing machines could not only apply and measure loads with great control and accuracy, but also the strains or extensions of test specimens under gradually increasing load. From this period, accurate determination of the stress-strain curve for a material became a more routine matter. Several academics, both in Britain and abroad, published books on materials testing and material properties, with particular emphasis on wrought iron and steel (for example: Box, 1883; Popplewell, 1901; Unwin, 1910; Smith, 1911). Each book is in part a compendium of the test results obtained by its author, together with a summary of results previously published by others.

5.3 Cast iron

5.3.1 Metallurgy and texture

Cast iron is an alloy of iron with around 2 to 5% of carbon, other elements being present as impurities that modify its properties significantly (Angus, 1976).

TENACITY OF WROUGHT IRON AND STEEL.

	Breaking Weights in Tons per Square Inch of			
	Original Section.		Fractured Section.	
	Highest Class.	Lowest Class.	Highest Class.	Lowest Class.
Steel bars for tools	59·3	45	62·1	59·1
„ „ rivets and bolts	47·9	41·1	70·9	62·2
„ „ puddled steel	31·9	28	49·7	31·8
Steel plates	44·3	32·3	51	35·7
Iron bars, Yorkshire	29·6	27	58·8	51
„ „ Staffordshire ..	28	24·7	65·4	33·6
„ „ Lanarkshire.. ..	28·9	20·8	52·6	21·4
„ „ Lancashire	27	24	46·6	38·5
„ „ Swedish	21·5	21·3	66·8	54
„ „ Russian..	25·3	22·1	34·7	32·2
„ „ Scrap	24·7	17·2	42	18·8
„ „ South Wales ..	17·2	13·2	17·6	13·3
Iron plate, Yorkshire	25·3	22	34	24·8
„ „ Staffordshire ..	24·1	20·3	27·4	22·3
„ „ Lanarkshire ..	22·9	18·6	27	19
Iron straps and angle-irons for strap building	25	18·5	30	20·5
Angle-iron, Lanarkshire ..	25	23·1	32	28
„ „ Staffordshire ..	25	22·3	31·9	26

Illustration 167 A summary of strength data obtained by David Kirkaldy (Source: Molesworth, 1867)

Chemical analysis of nineteenth century cast iron often shows a phosphorous content of 1 to 2%. Most modern castings have a phosphorous content of less than 0.5%, and as early as 1888 a writer suggested 0.2% as a preferred upper limit (Hooper, 1888). Phosphorous gives the molten iron greater fluidity, but the solid finished product is harder and less tough. Castings for structural work were usually made from a blend of different pig irons. 'Scotch Pig', with its relatively high phosphorous content, was best suited for casting intricate shapes with fine detail.

The cast iron found in old structures is invariably flake graphite or grey cast iron, in which carbon is present in both 'combined' and 'free' forms. Iron and some of the carbon combine chemically at high temperature in the furnace to form iron carbide or cementite. On cooling slowly from the molten state, thin layers of cementite are deposited between thicker layers of iron, forming pearlite, so named because of its mother-of-pearl sheen when viewed through a microscope. The remaining carbon does not combine with the iron but instead precipitates on slow cooling to form flakes of graphite.

Cast iron has low tensile strength, although in compression its strength is comparable with that of modern mild steel. It fractures as cracks propogate around the thin graphite flakes and then join to reveal a crystalline grey fracture - hence the term 'grey iron'. In broad terms, the tensile strength is inversely proportional to the amount of free graphite present. Graphite has a density of only 2250 kg/m^3, which is much less than that of pure iron, so a strong grey iron tends to be denser than a weak one. The average density of a typical nineteenth century cast iron beam is about 7100 kg/m^3.

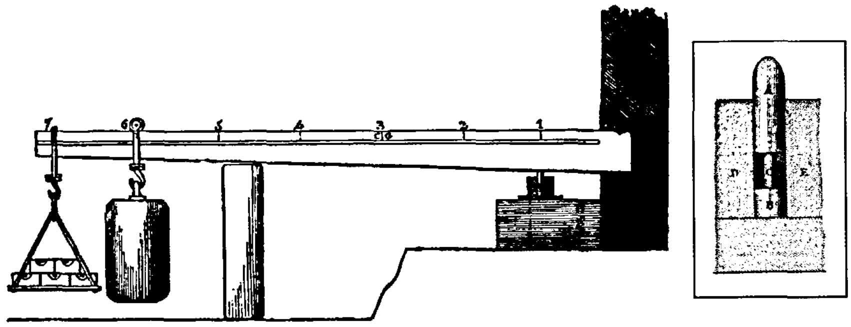
The mechanical properties of cast iron are dependent partly on the raw materials used in manufacture but also to a very significant extent on the rate of cooling of the casting. A metallurgist can gain more useful information from the microstructure of cast iron viewed under a microscope than from an analysis of its chemical composition. Thin parts cool more quickly than thicker parts and, when cast from the same melt, will solidify to form cast iron of greater strength and hardness. With very rapid cooling, or chilling, carbon will not form into flakes but instead remains 'frozen' within the crystal structure, forming a very hard and brittle 'white iron', not at all suitable for structural purposes. The presence of silicon as an impurity is beneficial for the formation of grey cast iron as it promotes the deposition of free carbon. Ductile or spheroidal graphite cast iron (known as SG iron) is a twentieth century innovation, in which the addition of manganese leads to the formation of spheres of graphite which, unlike graphite flakes, do not act as stress-raisers that cause brittleness.

5.3.2 Manufacture

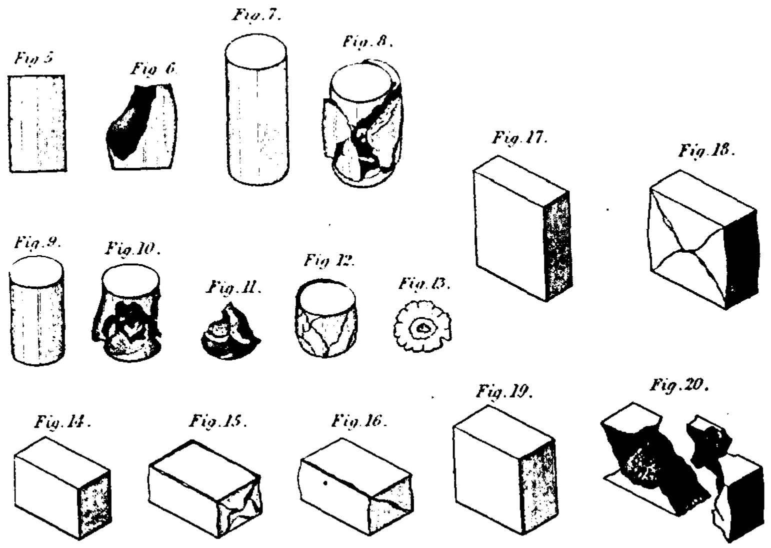
The iron masters produced different kinds of pig iron from the same ore by varying the quantity of fuel in the charge to the blast furnace and thus varying the smelting temperature (Rankine, 1869). The variation in strength between different pig irons was fairly large and not all were suitable or intended for structural applications.

No 1 pig iron was a grey cast iron produced with the greatest quantity of fuel and at the highest temperature, with a relatively high free carbon content in the form of graphite flakes. With a low melting temperature, No 1 iron was suitable for making fine and intricate castings where strength was not a primary concern. For structural applications, harder and stronger No 2 or No 3 iron was preferred, these being produced with rather less fuel. A still lower furnace temperature and less fuel would yield brittle white cast iron. White cast iron was not used for beams and columns, but could be produced as a hard wearing skin to a grey iron machinery casting by the use of metal mould linings to chill the surface. Specifications for structural cast irons sometimes included a minimum breaking weight for a small square or rectangular bar tested in bending.

For foundry castings, a blend of pig irons and scrap iron would generally be re-melted in a cupola or an air



(a) The force on the test specimen was applied using weights, the effect of which was amplified by means of a lever.



(b) Specimens after testing.

Illustration 168 Compression tests by Eaton Hodgkinson (Source: Swailes, 2004).

furnace for casting. Investigations into the relative merits of hot-blast and cold-blast iron were inconclusive. Hot-blast iron and in particular 'Scotch iron' developed a reputation for poor quality in some quarters. The hot-blast process certainly enabled large quantities of cheap iron to be produced from lower grade raw materials. Giving evidence in 1845 after the collapse of an iron-framed building, William Fairbairn described hot-blast iron as '*an exceedingly useful iron, either as regards mixing, or its working qualities for the finer descriptions of castings and light machinery*' (Royal Commission, 1845). For heavy castings, Fairbairn recommended a mixture of one-third hot-blast iron with about two-thirds of strong Welsh cold-blast iron. Fairbairn's opinion was 'every description of metal is improved by mixture'. In some cases an engineer would specify a particular recipe but more often the choice of mix would be left to the experience of the ironfounder. The engineer might specify instead the required minimum breaking strength of small bars tested in bending. For cast iron beams and girders, all might be proof-tested or else one extra might be cast and tested to failure.

One innovation in mix design was Morries-Stirling's 'toughened cast iron', for which the molten ingredients were cast iron blended with up to a quarter its weight of wrought iron scrap (Owen, 1847). Tests made in 1847 for the Admiralty showed that girders of toughened cast iron were, on average, almost 40% stronger than girders made to the same pattern from ordinary cast iron. No examples have been found of the use of toughened cast iron in Scotland, although the patentee had a North Berwick address.

5.3.3 Mechanical properties

(a) Compressive strength

Comprehensive mechanical engineering data on modern grey cast irons has been published by the British Cast Iron Research Association (Gilbert, 1977). The BCIRA data sheet for Grade 150 iron [see 5.3.3 (b)] gives values for ultimate compressive stress of 600N/mm^2 and a permissible direct compressive design stress of 156 N/mm^2. BD21 gives a permissible

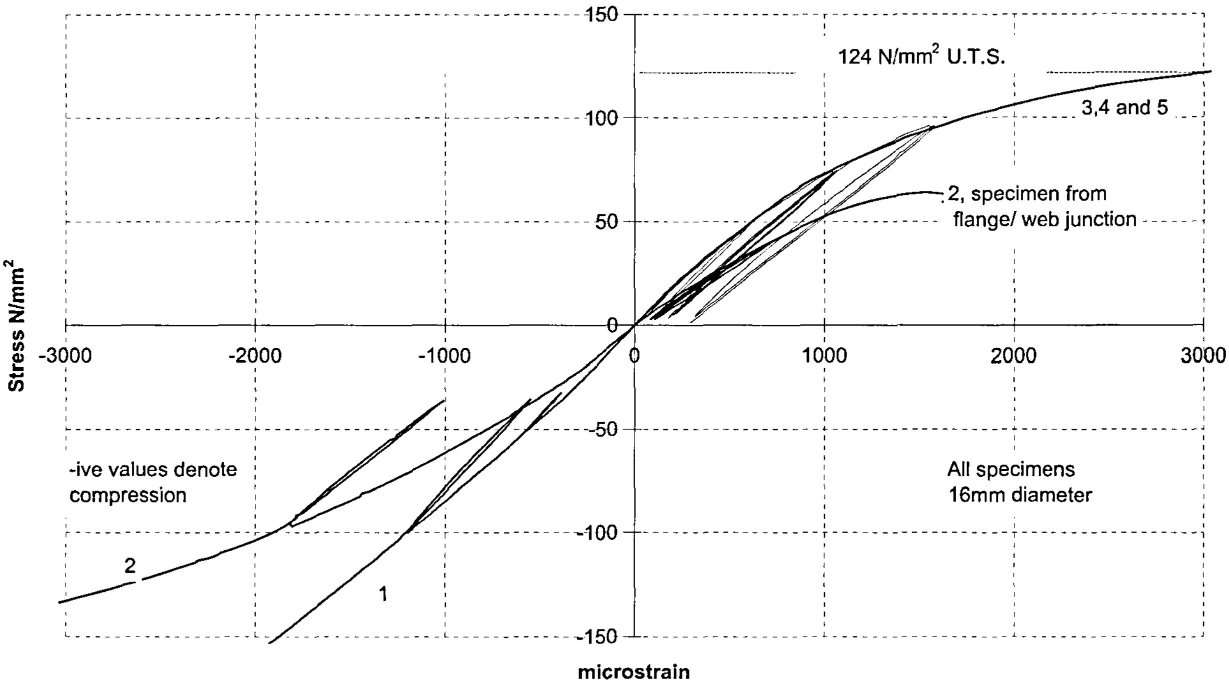


Illustration 169 Typical Stress-Strain characteristics of cast iron (Source: T. Swailes)

stress of 156 N/mm². BD21 gives a permissible compressive stress of 154 N/mm². For typical Victorian cast iron, the compressive strength is about 4 times the tensile strength, while for stronger modern cast irons, the ratio is nearer 3.

Test specimen shape is important for accurate determination of compressive strength. Satisfactory results have been obtained using cylindrical specimens with a length or height to diameter ratio in the range 1.5 to 3 (Illustration 168). As length and slenderness of a compression element are increased, a point is eventually reached where failure is by instability rather than by crushing of the material (See Section 6.4 'Columns and Struts').

(b) Tensile and bending strength

*BS 1452: N/mm²	1990 Grade tons/in²	Nearest 1961 Grade tons/in²
150	**9.7**	**10**
180	**11.7**	**12**
200	**12.9**	**-**
220	**14.2**	**14**
250	**16.2**	**17**

* replaced by European Standard BS EN 1561: 1997.

Illustration 170 Modern grades of grey (flake graphite) Cast Iron: Tensile and bending strength

In BS1452:1990, the modern standard for flake graphite cast iron, grades are determined principally on the basis of the tensile strength in N/mm² of a standard test bar cast with a diameter of 30mm. Prior to metrication, the grade numbers related to the tensile strength in tons/in^2. Most nineteenth century cast iron is of Grade 150, sometimes weaker. Grade 220 might be a rather exceptional nineteenth century iron, though a grade higher than this is routinely produced in modern foundries (Illustration 170). Mechanical tests are used in combination with careful examination of the microstructure of a polished and etched surface when determining the characteristics of a sample of cast iron.

The BCIRA data sheet for Grade 150 cast iron gives a permissible stress for direct tension of 38 N/mm^2, with a maximum of 23 N/mm^2 when designing for fatigue (Gilbert, 1977). BD21/97 gives a maximum permissible tensile stress of 46 N/mm^2 due to dead loads. This is reduced towards 20 N/mm^2 as the proportion of live load to dead load increases, allowing for the importance for bridge structures of dynamic loadings and fatigue.

It should be noted that the modulus of rupture of a small bar tested in bending, the strength of a tensile test specimen and the modulus of rupture of a large cast iron beam are not directly comparable, because of non-linear material behaviour and size effects (see Illustration 157).

(c) Deformation and stress/ strain characteristics

At working loads the response of cast iron structural elements will be only approximately elastic. For Grade 150 cast iron, the BCIRA data sheet gives a value for Young's Modulus of Elasticity E = 100 kN/mm^2. For the assessment of the axial or bending deformations of structural sections, the effective E value may lie in the range 80 to 120 kN/mm^2, the lower value being applicable for very large beam sections. Values obtained in tests on different types of structural cast iron sections, suitable for use in calculations based on elastic theory, are given in Section 6. Even at low levels of stress, loading and unloading cast iron will result in a small permanent set and a 'closed loop' on the stress-strain curve (Illustration 169). The stress-strain characteristics of grey cast irons are considered in some detail by Angus (Angus, 1976).

In elastic materials the theoretical value of Poisson's ratio v is 0.25, but the response of cast iron is non-linear, particularly in tension. Tests on a Grade 220 iron showed that Poisson's ratio decreased linearly from the theoretical value of 0.25 at a very low tensile stress to about 0.14 close to the ultimate tensile stress. A value of 0.22 therefore approximately represents the working tensile stress condition, while in compression a value of 0.25 is applicable over the normal working stress range (Angus, 1976). For practical purposes this may be too refined. According to Gilbert, an initial Poisson's ratio of 0.26 may be taken for grey cast iron and, given the relation between the material elastic constants, the Shear Modulus (or Modulus of Rigidity) G may be taken as 0.4E (Gilbert, 1977).

(d) Hardness

According to the modern standard BS1452, the grade of grey cast iron can be determined either directly in a tensile test, or indirectly estimated by means of a Brinell hardness test. However, nineteenth century irons often have a high phosphorous content which, according to an authority quoted by Angus (1976), leads to an increase by 30 points Brinell for each 1% phosphorous. Ignorance of chemical composition may lead to a significant over-estimate of the grade of old cast iron, if based on the BS1452 hardness correlation.

In the hardness test, performed using a standard piece of laboratory equipment, a steel ball is pressed into the smooth surface of the test material by a known mass for a standard period of time. The alternative Vickers hardness test uses a diamond pyramid indenter. Up to hardness numbers of about 300 HB, very rarely exceeded in nineteenth century grey cast irons, the Vickers hardness number (HV) and the Brinell hardness number (HB) are nominally the same.

Portable hardness testers are available, but may give misleading indications because of 'skin effects'. Material at the surface of a casting, where cooling is more rapid, will be harder than material at the centre. Other mechanical properties will vary in a similar fashion through the thickness of a large casting (Illustration 171).

(e) Toughness

As a brittle material, cast iron has poor resistance to impact loads. Several simple impact tests were developed early in the twentieth century to identify steels vulnerable to shock loading, where no such problems could be detected by a normal tensile test (Salmon, 1931). In the Charpy test, a simply supported beam notched at mid-span on the tension side is struck by a hammer pendulum. The Izod test works on a similar principle, with the energy absorbed determined from the height to which the pendulum swings after fracturing a notched cantilever beam specimen. For energy absorption values less than 95 Joules, Charpy and Izod values are for practical purposes the same. For modern Grade 150 to Grade 220 modern cast irons, Charpy values of 8 to 16 Joules are to be expected for 20.3mm diameter bars (Angus, 1976). However, when the phosphorous content exceeds 0.7%, often the case with nineteenth century cast iron, lower Charpy values are likely even when the tensile strength is high.

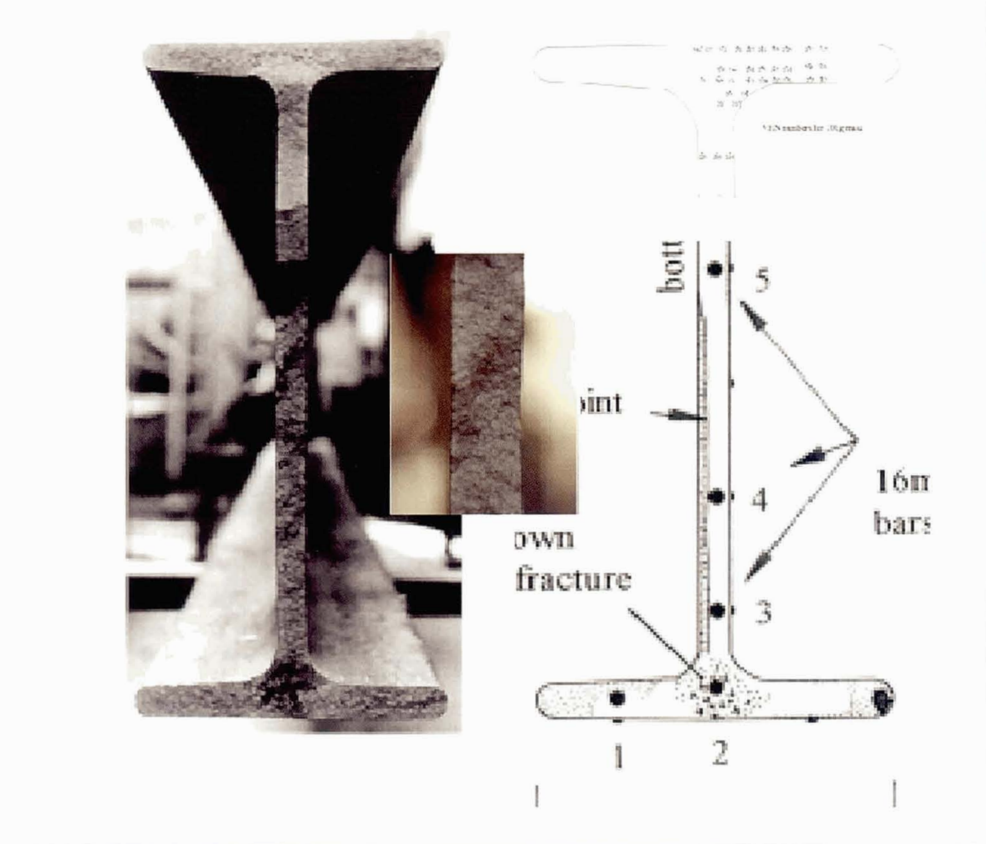


Illustration 171 Hardness and tensile strength variation across a large cast iron I - section (Picture: T. Swailes)

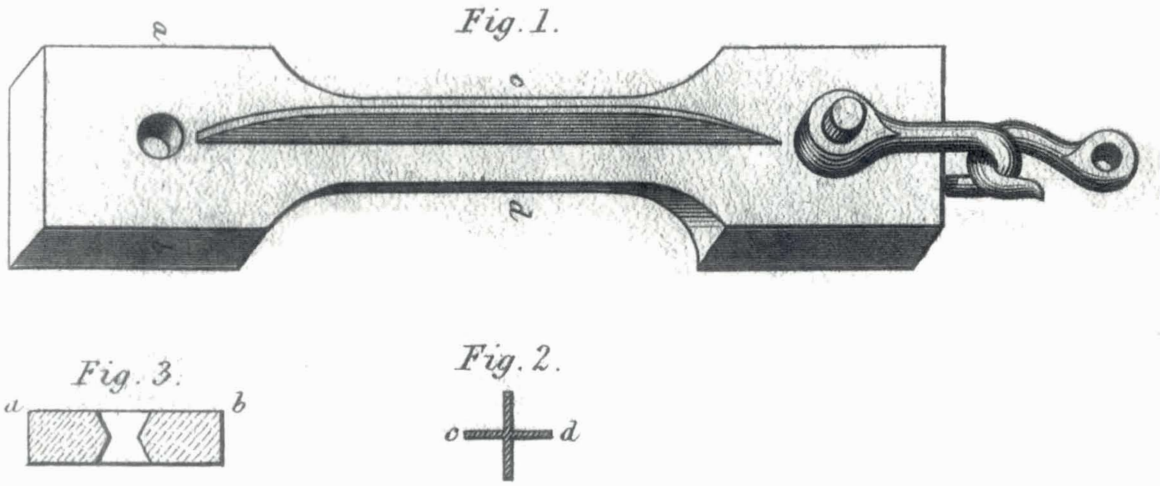


Illustration 172 Tensile test specimen (Source: Hodgkinson, 1846) This form of specimen was devised to ensure concentricity of loading

When fracture mechanics is used in a structural assessment to determine the effect of defects on strength, the material property 'plane strain fracture toughness' (K1C) is required. For samples from large nineteenth century beams of low grade cast iron from two different sources, values for K1C were obtained in the range 11.5 to 16.9 $MN/m^{3/2}$ (Parmenter, 1997). Phosphorous contents were 0.9 to 2%.

5.3.4 Temperature dependency of material properties

Cast iron resists extremes of temperature rather better than do wrought iron and steel, but at normal temperatures has a similar coefficient of thermal expansion of 11×10^{-6} per °C. The impact resistance of grey cast iron reduces by only 30% with a fall in temperature to -100°C, so seasonal low temperatures do not have a very marked effect on structural cast iron.

Grade 180 iron with a phosphorous content of around 1% has better dimensional stability at high temperatures than low phosphorous material (Angus, 1976). Up to about 600°C, it is resistant to scaling (the progressive destruction of the casting surface by oxidation or other chemical attack), and it remains today a useful material for fire-bars and grates. Plastic creep will occur at temperatures above 400°C, even at relatively low stress levels (see also Section 7.5.1). At higher stress levels, creep will continue until failure. Under long term loads at high temperature, the loss of strength at 350°C is not significant, at 500°C the strength reduces to about $^1/_4$ of its original value and at 800°C there is little residual strength. On cooling after exposure to temperatures of 600°C for several hours, cast iron shows no significant loss of strength (Kirby, 1986). However, a permanent loss of strength results on cooling from 750°C, sometimes as much as 50%.

5.3.5 Historical test data and materials testing

The results of the very earliest tests in compression are unreliable because the significance of test specimen shape and size was not understood. In a cubic compression test specimen, the material is placed in a complex stress state and appears stronger because of friction developed across the loaded faces. The ironfounder William Reynolds wrote to Thomas Telford in 1801 with the information that '*a cube of $^1/_4$ of an inch square of soft or gray cast iron resists a pressure of 80 cwts before it gives way and crumbles into small pieces...*'. This equates to an ultimate compressive stress of 989 N/mm^2, much higher than the possible true value for the material compressive strength. Telford carried out many tests on cast and wrought iron in 1814 that were disseminated in influential 'strength of materials' books by Peter Barlow in 1817 and by Thomas Tredgold in 1822.

Suitable forms for compression test specimens were eventually determined by Eaton Hodgkinson in Manchester (see Illustration 168). Hodgkinson also endeavoured to achieve a specimen and grip arrangement that delivered a perfectly concentric pull in tensile tests on cast iron (Illustration 172). Bending tests were easier, and a bending test on an inch square test bar cast alongside the main casting was used for quality control purposes for much of the nineteenth century. The bar was laid horizontally across simple supports spaced several feet apart and loaded at the centre until it broke. The large difference between the 'modulus of rupture' of a bar in bending and the tensile strength has already been referred to in Section 5.3.3 (b).

6 STRUCTURAL ELEMENTS

6.1 Introduction

This section is concerned with the characteristic features and structural properties of wrought iron and cast iron elements in tension, compression and bending. The influence on structural properties of method of manufacture and of defects is considered. Present day guidance on the assessment of element capacity is reviewed and placed in its historical context. Historical test data is of particular relevance because, in the absence of much modern data on structural iron, we rely upon it to a considerable degree in our present day methods of assessment. Both forces and vertical or lateral deflections could be measured with good accuracy in the nineteenth century, so most reports of tests on structural elements from this period are reliable.

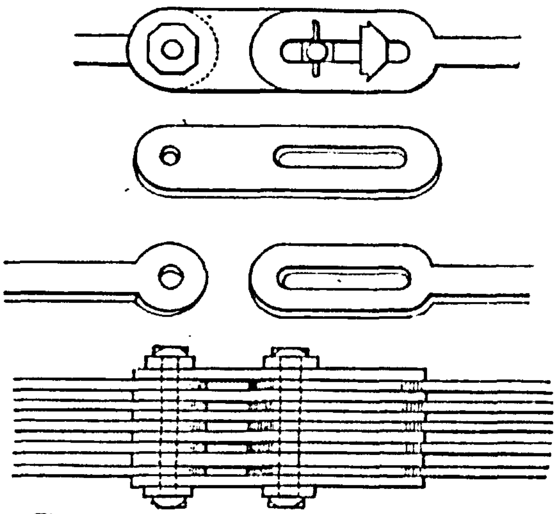


Fig 514. UPPER LINKS AND JOINTS.

Illustration 173 Menai Suspension Bridge (1826): bar-chain and coupling link details
'The iron was of the best Shropshire manufacture, supplied from Upton Forge, by Mr. Hazeldine of Shrewsbury. The bars were repeatedly drawn between cast iron rollers, grooved in various shapes, and afterwards proved at the works (to a tensile stress of 11 tons/in^2), previous to being shipped for the Menai Straits'. A typical chain-bar was 10 feet long with a 3^1/$_4$ in. × 1 in. rectangular cross-section and end connections to facilitate tightening (Source: Cresy, 1847).

6.2 Wrought iron ties

6.2.1 *Details and manufacture*

Pre-industrial wrought iron bars used in decorative work and for tying and pinning structural masonry or timbers were formed entirely by hammering at a white heat, with scarf-type lengthways joints made by forge welding. By the early nineteenth century, bar iron for structural purposes was rolled, with critical tension members being made from superior quality material.

The specification for the chain-bars for Telford's Menai Bridge, built between 1819 and 1826, was described by Edward Cresy (Illustration 173). Captain Samuel Brown had patented his ideas for suspension bridge building in London in 1817 and in Edinburgh a year later (Day, 1983). Brown adopted a variety of bar and link details in his different bridges. It was normal practice to make the straight length of either a round or a rectangular bar and its terminal eyes separately and then weld them together. Brown at first advocated punching the holes in the flat link plates but later stipulated that they should be drilled (Illustration 174 and 175).

Several early Borders suspension bridges used higher strength iron wire instead of bar iron. Wire manufacture was described in a contemporary Cyclopaedia (Rees, 1820). First, the end 6" to 8" of a large bar was heated at the forge. This short length was hammered out into a uniform round rod of 5' or 6' in length under a small 50 pound tilt hammer, delivering around 20 strokes a minute. The rod was then cut from the bar and its tip further reduced by hammering on an anvil, for pulling or drawing through a holed plate. The wire was annealed after each pass through progressively smaller holes in the draw-plate. Mechanical properties depended on the extent to which the effects of cold working in drawing out the wire were countered by annealing.

6.2.2 *Strength and assessment*

A permissible tensile stress of 77 N/mm^2 (5 tons/in^2) was in general use for the design of wrought iron in railway bridges in the second half of the nineteenth century. This gave a factor of safety of over 4 on ultimate stress, or about 3 on the yield stress of 220 N/mm^2 now specified in BD 21. The manufacturing process produced differences in the ultimate strengths of different types of section that are not generally taken

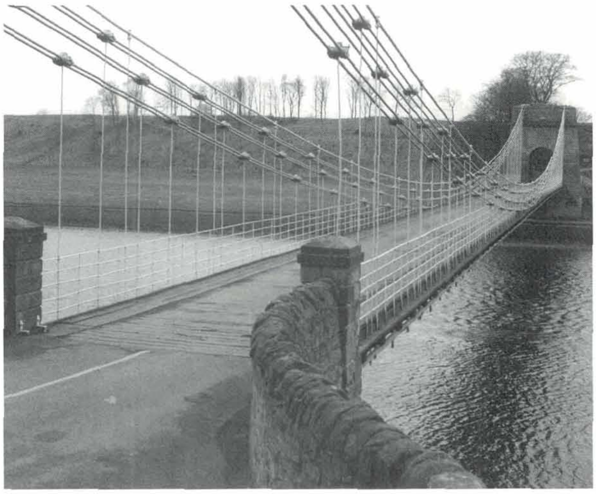


Illustration 174 Union Bridge, near Berwick (1820) General view (Picture: Crown Copyright: RCAHMS. Reproduced courtesy of JR Hume)

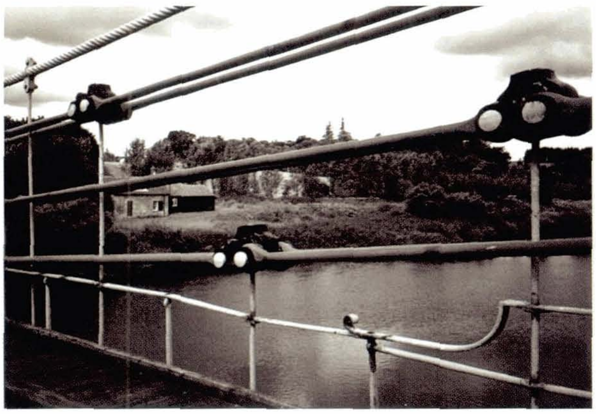


Illustration 175 Union Bridge, near Berwick (1820) Chain details Each chain-bar consists of a 2 in. diameter wrought iron bar 15 feet long with a forged and welded eye at both ends. The original roadway suspension system, now supplemented, consisted of three tiers of chains with vertical suspender bars of 1 in. diameter spaced 5 feet apart. (Picture: T. Swailes)

into account in assessment. According to the engineer for the Skerne Iron Works in Darlington, the commoner brands of (plate) iron would bear 20 tons/in^2 (309 N/mm^2) along the grain and 18 tons/in^2 (278 N/mm^2) across the grain (Hutcheson, 1879). Tee and angle sections, often used for tension members, would be about 2 tons/in^2 (31 N/mm^2) stronger. For bridges subject to dynamic loads, the use of a relatively low permissible stress generally proved to be a satisfactory safeguard against fatigue failure, a phenomenon still not fully understood in the 1880s (Fidler, 1887). The fatigue endurance limit for wrought iron has been found to be about one third of the elastic limit or yield stress (Cullimore, 1967).

Use of the full tensile capacity of a tie bar (see 5.2.3 a) depends on the end connections being at least as strong as the bar. High stresses and poor end details were a common factor in suspension bridge failures from the 1820s onwards. These failures influenced engineering practice in two ways. Firstly, early optimism with respect to safe working stresses was replaced by a more cautious approach. Secondly, experiments were carried out with the aim of finding efficient and safe forms of tension member end connections.

At the time of the design competition for the Clifton suspension bridge it was commonly believed that a small bar of wrought iron tested in tension would yield at about 13 tons/in^2 (201 N/mm^2) and break at about 23 tons/in^2 (355N/mm^2) (Pugsley, 1976). A wide range of design stresses was proposed, from 4 to 10 tons/in^2 (62 to 155 N/mm^2). Brunel himself proposed design stresses of 8 tons/in^2 (124 N/mm^2) in 1829 and 6½ tons/in^2 (100 N/mm^2) in 1830, before settling for 5 tons/in^2 (77 N/mm^2) in 1838. Brunel's first design used chain-bars of 12' in length. These were also called links, being without the intermediate short linking pieces used by Brown and Telford. Improvements in manufacturing enabled Brunel to specify 20' long chain-bars by 1838.

Ewing Matheson wrote of such structures in 1873 that 'the links which compose the chain were formerly manufactured by welding the heads to a flat bar; and the proportions of the heads are in most of the old bridges imperfect. At the present time the link is always rolled together with the heads in one piece, and the proportions of the head have been improved' (Matheson, 1873).

In 1967, the Point Pleasant Bridge (or Silver Bridge) over the Ohio River in the USA collapsed due to corrosion-fatigue failure at the eye end of a steel suspension chain-bar. This prompted a structural assessment of the Hungerford Bridge chains that had been reused for the Clifton Suspension Bridge (Bulson, 1983). A finite element analysis showed that the original proof-loading specified by Brunel to check the strength of the weld between the bar and the eyes would have caused localised yielding in the eye at its bearing with the connection pin. Theoretical analysis was accompanied by strain measurements on the bridge and, under laboratory conditions, by tests on a full-size replica of the eye-bar end. It was concluded that the residual compressive stresses remaining in the eye after proof-loading were effective protection against fatigue due to live load stress variations. Separate tests on wrought iron suspender rods from the bridge showed that the forge-welding of the eyes was at least 85% efficient (see Section 5.4).

Results have been reported of a fracture critical study of the eye bar connections to a trussed wrought iron bridge in Texas (Badoux, 1998). The bridge, built in 1887, at one time carried pedestrian and vehicular traffic, but was to be refurbished in 1998 for pedestrian use only. Tension members were up to 25mm x 100mm rectangular section and the connecting pins from 50mm to 100mm diameter. Material sampling and testing provided data for a linear elastic fracture mechanics analysis, from which critical crack sizes of over 13mm were calculated for the pins and eye bars. The critical crack or flaw size is the size at which a crack will propogate under the applied stresses, leading to fracture. Trials showed that flaws smaller than 5mm could be detected by ultrasonic testing using low frequency transducers. Ultrasonic testing of the fracture critical eye bars and pins in the bridge showed them to be in good condition and repairs were needed only to remedy limited corrosion deterioration.

Ultrasonic testing has been used in Italy to locate and characterise sub-surface discontinuities in forged sixteenth century wrought iron (Bartolini, 1997). Surface stress-related cracks were detected using a magnetic particle technique. Concentrations of magnetic field lines at discontinuities (at or close to the surface) are made apparent by heaping of magnetic powder.

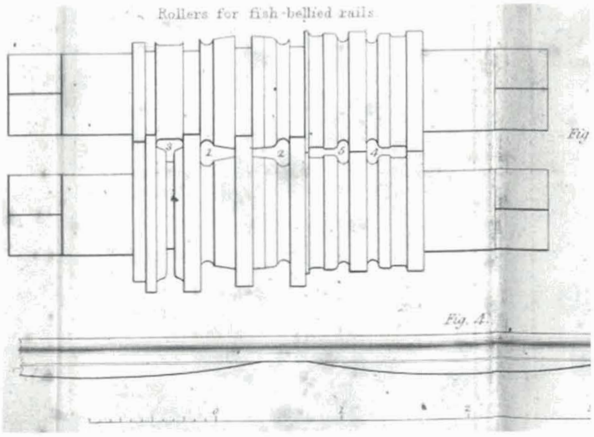


Illustration 176 Rolls for fish-bellied wrought iron rails Reproduced from 'Strength of Materials' (Barlow, 1837). Barlow described the working of the rolls thus: 'The iron is first drawn down to a square bar of a proper size; it is then passed successively through the rollers, as numbered in the figure'. The rail was passed on its side through all the grooves between the rolls except for groove No. 3, where 'the lower cylinder is turned eccentric to the axis of the rollers, so that as the iron passes on it is rendered of different depths, as shown in Figure 4'.

6.3 Wrought iron beams

6.3.1 Rolled sections - development, details and manufacture

(a) Glazing bars

The structural use of wrought iron in the first quarter of the nineteenth century was rather limited, despite the innovations of Henry Cort and others (see Section 2.3). The small sections available were too slight to compete with timber or cast iron for joists, beams and girders. One structural application was the sash-bar or glazing bar, invented by J C Loudon in 1816 (Gloag, 1970). These were made by passing heated plain iron bar through profiled rolls.

(b) Rails

The success of the passenger railways was a spur to further development. Wrought iron rails, unlike cast iron, were not prone to fracture with potentially catastrophic consequences. The pioneering 'Darlington Wrought Iron Railway' opened in 1825 generated international interest (Oyenhausen, 1829). In the two decades following its completion, the astonishingly rapid development of more powerful and heavier locomotive engines made a stronger permanent way necessary. The original rails for the Liverpool and Manchester Railway of 1829 were rolled in 15' lengths, spanning 3' between stone bearing blocks and weighing 33 lbs/yard (16 kg/m) (Ferneyhough, 1980). An ingenious arrangement enabled rails to be rolled with an economical 'fish-bellied' longitudinal profile between supporting stone blocks (Illustration 176).

Heavy parallel rails of 75 lbs/yard (37 kg/m) were first tried prior to 1837 on some sections of the London and Birmingham Railway (Lecount, 1839). F S Williams commented on the problems of making large sections; 'difficulties have, until lately, existed in the rolling out of such heavy rails at the manufactories; but the improvement of machinery now allows of their being prepared with greater facility and at a less cost' (Williams, 1852). Our present day system, with parallel rails laid across closely spaced sleepers on a bed of stone ballast, became the preferred form of permanent way construction only after 1850.

The life of rails depended very much on the quality of the wearing surface, with laminar wrought iron tending to wear unevenly and to smear, unlike more uniform steel. Submitting a tender for the supply of rails in 1865 to the Great Northern Railway, the Darlington Iron Works gave some details of the materials to be used and the processes involved (Brooke, 1999). First a 10" x 10" pile of bars was set up, the top and bottom bars being 'pure mine iron' and the interior bars puddled Yorkshire pig iron. The pile was hammered hot under a 5 ton steam hammer and 'wrought on all sides and upset in every direction'. The resultant mass was then hammered under a 6 ton hammer at welding temperature to form compact blooms, for rolling into bars and then rails. Worn out or redundant rails (from both railways and tramways) are sometimes found in buildings, reused as lintels or in filler joist floors, for example.

(c) Deck beams

In 1844 James Kennedy and Thomas Vernon of Liverpool patented several forms of deck beam for use in the construction of ships (Gale, 1965). Descriptions included 'iron rolled in one piece having a flange on one edge projecting on one or both sides, and a rib or flange on the other edge, projecting on one or both sides'. Deck beams were used by Richard Turner of the Hammersmith Iron Works, Dublin, for the main ribs to the 1844-48 Palm House at Kew Gardens (Minter, 1990). The ribs, with a 'bulb' lower flange, were rolled in relatively short lengths which were joined, presumably, by forge welding with the assistance of a Nasmyth steam hammer. Turner used deck beams in several other roofs. For the arched truss roof to Liverpool Lime Street Station, 9" deep deck beams in 24' lengths were joined together by riveted web and upper flange plates. Similar joint details were used for a bow-string roof of 70' span to a 700' long quayside transit shed in Glasgow, in which the radial strut members were of cast iron (see Illustration 73).

(d) Joists (with equal flanges)

The next development was the rolling of joist sections. William Fairbairn reported tests on three malleable (i.e. wrought) iron I-section deck beams in 1845, giving no information on how they were made (Fairbairn, 1849). With the making of rails a lucrative business, manufacturers probably had little incentive to diversify. Hoping to use wrought iron joists instead of cast iron in 'Fox & Barrett' flooring, James Barrett was obliged in the early 1850s to ask a manufacturer to make rolls especially for him (see Section 7.4.3). Through most of the second half of the nineteenth century and on into the twentieth century, imports of rolled structural sections from Europe were very significant, first iron and later, steel. In 1880, at least one British manufacturer, Bolckow, Vaughan & Co., of Middlesborough, was rolling steel beams for about the same price as wrought iron, but 30% more expensive than Belgian beams (Kennedy, 1880).

6.3.2 Riveted sections - details and manufacture

In the eighteenth century, boilers for Newcomen engines had been made by manually riveting together plates hammered out of wrought iron and rarely weighing more than 50 lbs each (Jenkins, 1918). In 1838, before Nasmyth's invention of the steam hammer, Mechanic's Magazine considered it truly exceptional that the Coalbrookdale Company could

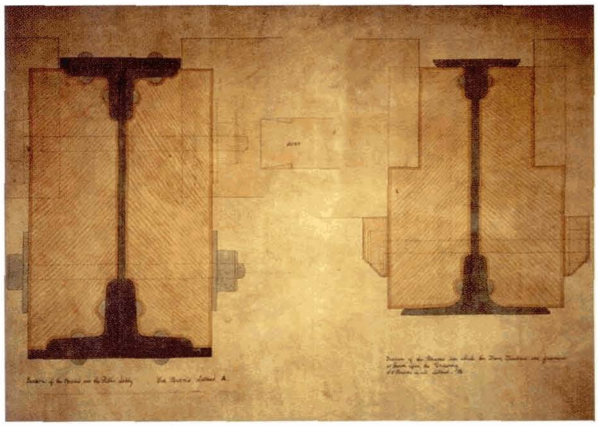


Illustration 177 Edinburgh Post Office (1859)
Riveted wrought iron girder, with timber cladding providing concealment and fire protection (see also Illustration 277)
(Picture: National Archives of Scotland)

make wrought iron plates of 10' -7" × 5' -1" × $^7/_{16}$" thick. A year earlier, William Fairbairn had developed a riveting machine for use in boiler making by adapting a hole punching machine (Fairbairn, 1877). Although this gave a ten-fold increase in productivity, wrought iron sections formed by riveting together rolled angles and 'boiler plate' remained expensive in comparison with cast iron.

Boiler plate girders were used in a number of Edinburgh buildings from the late 1850s (see Section 3.2.5 and Illustration 19) (Illustration 177). After about 1850, standard 'rules of thumb' were used increasingly in the design and detailing of joints. The combined cross sectional area of the rivets in a joint would be approximately equal to the cross sectional area of the plate left after punching or drilling the rivet holes. The rivet diameter would generally be 2 × the plate thickness for plates less than $^1/_2$" thick. For thicker plates, the rivet diameter would be about $1^1/_2$ × the plate thickness (Rankine, 1869). For girders, the pitch of the rivets (or spacing between their centres) was commonly 3" or 4", or 5 × the rivet diameter, and not less than $2^1/_2$ diameters (Rivington, 1876). The width of a rivet head is typically 1.5 or 1.6 times the diameter of the rivet. Mechanical riveting was faster and structurally superior to manual riveting.

6.3.3 Strength and assessment

Generally, the stress values adopted for the assessment of beams are those adopted for the assessment of tension members (see Section 6.2.2). The yield stress for wrought iron is the same in tension and compression, but the permissible or allowable flexural compressive stress is reduced as necessary to prevent lateral-torsional buckling, in the same manner as for steel beams.

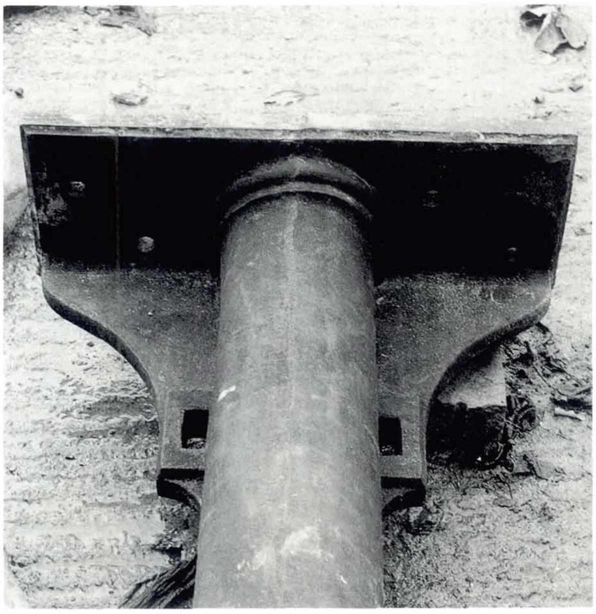


Illustration 178 Cast iron column top with a vertical bolting face and a seating projection for a bracket (Picture: T. Swailes)

Illustration 179 Cast iron column top (other side) with horizontal bearing table (Picture: T. Swailes)

An architect might specify a rolled wrought iron joist by simply noting the depth required on a plan. Sometimes the breadth (of the flange) would be specified too. Iron joists would be bought by a builder from a merchant or stockholder, but engineers were scathing about the quality of such loosely specified 'builders ironwork' (Reade, 1890). However, joists were generally used in buildings as they came, straight from the rolls, any holes being drilled rather than punched. Under these circumstances, Professor Kennedy of University College, considered that harder and less tough material, of a kind not suitable for 'engineering structures', might be satisfactory (Kennedy, 1880).

The satisfactory rolling of joists was more difficult than that of plates, bars, angles or tees. A metallurgical investigation of one of the first wrought iron I-beams rolled in the United States confirmed the inhomogeneous nature of the material and the presence of strength reducing defects (Elban, 1998). There was evidence to suggest that after rolling, supplementary material was added to form the flanges, resulting in a crack across one flange. Lack of toughness was also found in tests on wrought iron joists from the Royal Albert Hall (see Illustration 157). There has been one report in recent years of the brittle failure of a rolled wrought iron beam, in a building in Yorkshire. The beam was 10" to 12" in depth and of relatively short span. A sloping fracture towards one end suggested that shear played a part in the failure, which caused injuries to two men carrying out work on the building (Bland, 1984).

Stress values based on sampling and testing should not be used for the assessment of wrought iron joists, unless tests confirm material toughness on a par with modern mild steel. Likewise, assessment should be based upon elastic rather than plastic methods of analysis. For the assessment of riveted wrought iron, the area of rivet holes should be deducted when determining tension flange stresses. Fatigue and fracture assessment of wrought iron bridges has been the subject of work in Germany over the past 25 years. Several papers are listed under the heading 'Modern testing and repair', in a reading list published by the Institution of Civil Engineers (Chrimes, 1994).

6.4 Cast iron columns and struts

6.4.1 Details, manufacture and defects

Circular hollow section columns with an outer diameter of up to about 300mm, as common in buildings, were normally cast horizontally. The earliest cast iron columns, little more than storey posts, are of cruciform or quatrefoil solid section. Later columns of small diameter may be solid, but were more often made hollow by the use of a core supported at the centre of the mould. A column core consisted of a tube or bar, wound with coarse rope, plastered over with wet moulding material, then oven-dried before use. The core required supports below at intervals along its length as well as supports above to prevent flotation on entry into the mould of the dense, molten iron.

The position of the column mould joint is often clearly visible up the sides of a hollow circular cast iron column. Blowholes to one face may indicate the surface that was cast uppermost. Generally such

Illustration 180 Cast iron column cross-sections, showing defects: core eccentricity, voids and porosity (Picture: T. Swailes)

Illustration 182 The Grassmarket, Edinburgh (1875)
A bent cast iron column supporting lintels over a shop front (Picture: T. Swailes)

Illustration 181 Cast iron column cross-sections, showing defects (Picture: Joe Marsh, UMIST)

defects have no structural significance. Requirements for features such as drive-shaft bolting faces often determined the orientation of the column in the mould (Illustrations 178 and 179). Movement of the core within the mould was common and most columns suffer from core eccentricity to a greater or lesser degree (Illustrations 180 and 181). This does not much affect load-carrying capacity (the cross-sectional area being unaffected), but wall thickness needs to be measured at several points around the circumference in order to determine an average for purposes of calculating cross-sectional area. This may be done via drilled holes or non-destructively, using ultrasonic measuring techniques. A small degree of curvature or lack of straightness arising from imperfect manufacture is quite normal, but where curvature is clearly visible, overload or accidental damage should be suspected (Illustration 182).

Illustration 183 Glasgow Green (probably c.1850) Shop front framing during demolition (Picture: T. Swailes)

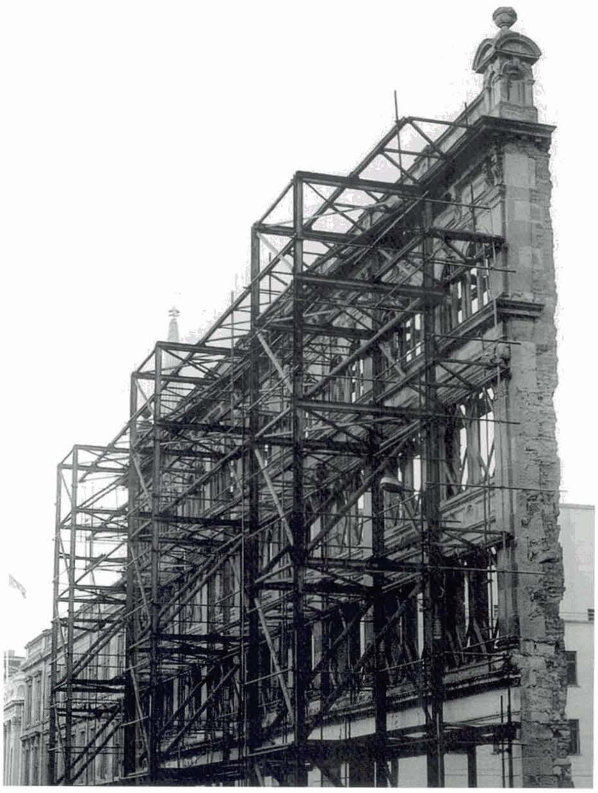


Illustration 184 Ingram Street, Glasgow (c.1854) Front view of a façade retained for inclusion in a future development (Picture: T. Swailes)

Illustration 185 Ingram Street, Glasgow (c.1854) Rear view of a façade retained for inclusion in a future development (Picture: T. Swailes)

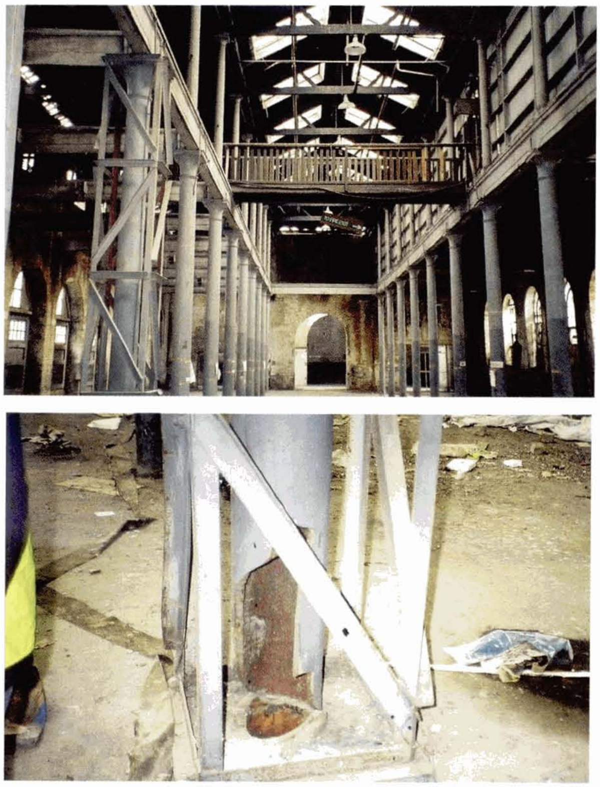


Illustration 186 Former Rail Store, Gidea Park, Essex (above) Internal view (below) Detail
A 'historic repair', with a replacement column of light angle truss construction providing vertical support to an overhead crane rail support beam. The badly damaged hollow circular cast iron column was left in place, still supporting the roof (Picture: Morrison Construction)

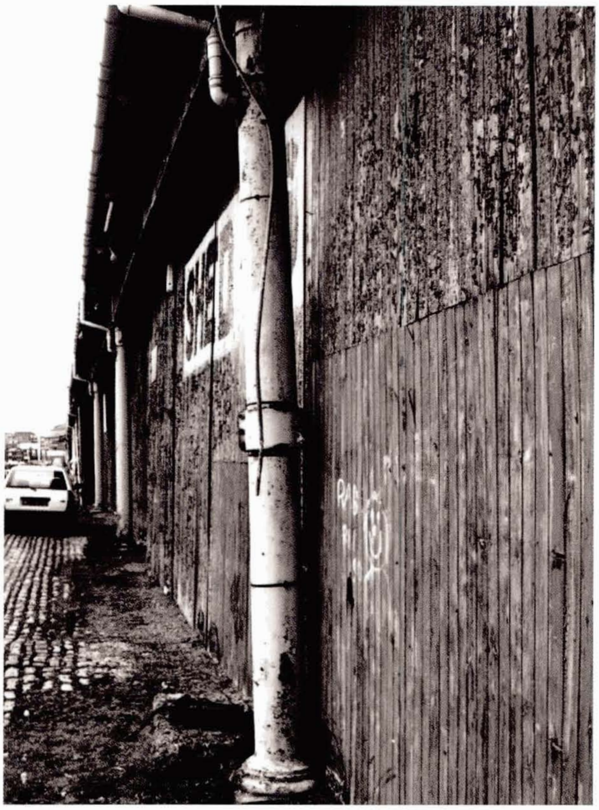


Illustration 187 Dockyard Transit Shed, Victoria Dock, Dundee (1874) Fractured quayside column (Picture: T. Swailes)

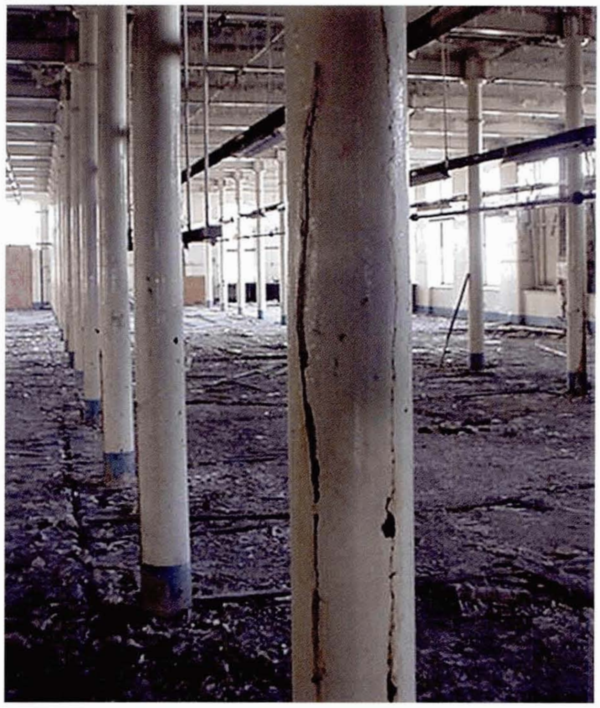


Illustration 188 Domestic Finishing Mill, Anchor Mills, Paisley (1889) Cast iron columns split by ice. Several columns became filled with water due to a defective flat roof. The water in the columns froze over winter in the semi-derelict building, which was largely open to the elements. (Picture: Buro Happold)

Mid-nineteenth century shop fronts were often framed in cast iron. Exposed columns are usually circular, but concealed columns take a variety of forms (Illustrations 183 to 185). Hollow circular columns of very large diameter, or piers as used in railway bridge construction for example, were generally made in thin-walled sections. These would be cast vertically in loam moulds (formed using brickwork and without patterns) and joined via spigoted ends and/ or internal bolted flanges. Often such sections were filled with brickwork or rubble. Cracking may occur as a result of corrosion and expansion of fixings, or due to restrained thermal movements.

Columns were vulnerable to impact damage where moving of heavy items by crane took place. Engineering workshops or foundries were generally served by overhead cranes, while dockside goods were handled by mobile rail-mounted cranes (Illustrations 186 and 187). Sometimes a problem will be immediately apparent, but columns in such positions should always be examined carefully for 'historic' damage. The large I-section columns of the great engineering workshops of the second half of the nineteenth century were moulded and cast in the same way as beams, often with holes in the web to reduce section weight. Their projecting flanges were generally left unprotected (see Illustrations 254 and 255).

In cast iron columns that have served as rainwater pipes, localised internal corrosion may be severe, and its extent difficult to determine. Where columns are not sealed, they may become filled with water, which then has nowhere to drain. To find water in hollow columns is by no means unusual. Vertical splits were found in a significant number of columns when structural engineers inspected the derelict Domestic Finishing Mill at Anchor Mills in Paisley (Illustration 188). Drilling holes in other columns to determine wall thickness, they were found to be partially filled with water, drained from the defective roof. The building was largely open to the elements over winter, and it appeared that water in the columns had turned to ice. Splitting had been caused by the expansion associated with freezing. One nineteenth century report has been found of a cast iron column 'exploding' as the result of ice formation within. More recently, the problem has caused the splitting of the hollow tubular legs of steel towers.

6.4.2 Strength and assessment

The load capacity of cast iron columns and struts is generally estimated using the Gordon-Rankine formula. Lewis Gordon, W J M Rankine's predecessor as Professor at Glasgow University, devised the formula as a semi-empirical fit to the results of a remarkable series of experiments by Eaton Hodgkinson (Illustrations 189 to 191). Rankine generalised the formula by expressing slenderness in terms of effective length and radius of gyration. For assessment purposes, the BD21 version of the formula includes a factor of safety of 5. Where load is applied eccentrically, a check of bending stresses is made, although arguably a factor of safety as large as 5 gives some allowance for nominal eccentricity.

Recently, Historic Scotland has supported research at UMIST to extend the work that Hodgkinson began over 160 years ago. Several hollow circular column sections from outbuildings at Stanley Mills became available for testing after a fire. The longitudinal profile and cross-sectional details of each slightly tapered column was measured with great care (Illustration 192). Nominally they were of 5" outside diameter.

The test on pin-ended Column 1 was carried out in three stages (Illustration 193). With an initial unloaded curvature giving a maximum lateral offset w of 7mm, the column was loaded concentrically to 620 kN. After unloading, the column was displaced laterally in the testing frame at both ends to give an eccentricity of 10mm, its curvature also having increased through plastic deformation to w = 9.5mm. After a second cycle of loading and unloading, a hole was drilled in the tension face of the column at the point of maximum lateral offset w. A normal hacksaw blade was used to cut slits either side of the hole, then the blade was ground as thin as possible and used to extend the slits to simulate a crack (Illustration 194). The column was then loaded to failure. Column 2 was tested in two stages, the second stage involving loading to failure with an eccentricity at both ends of 50mm (Illustration 195).

Using the Gordon-Rankine formula, with a factor of safety of 5, gives an approximate working load for the test columns of 100 kN. Numerical elastic analyses were carried out for each column, allowing for the P-delta (large displacement) effect. A reasonable fit was found between the experimental and theoretical results, except for the large eccentricity test on Column 2. In this case, part of the column section was subject to bending tensile stresses from the start of the test over the length of the column. A better theoretical result requires account to be taken of the non-linear material behaviour of cast iron in tension.

In practice, finite element analysis will be useful in the assessment of cast iron columns only if their end conditions and the eccentricity of load are known, or can be determined by site testing. Research is continuing into this area of uncertainty. Nineteenth century practice in column design was by no means uniform with a variety of design methods used, and with factors of safety varying from 4 to 10. In 1904, the Darlington Apartments in New York collapsed at a late stage in construction. Afterwards, cast iron columns were not trusted for high-rise construction in

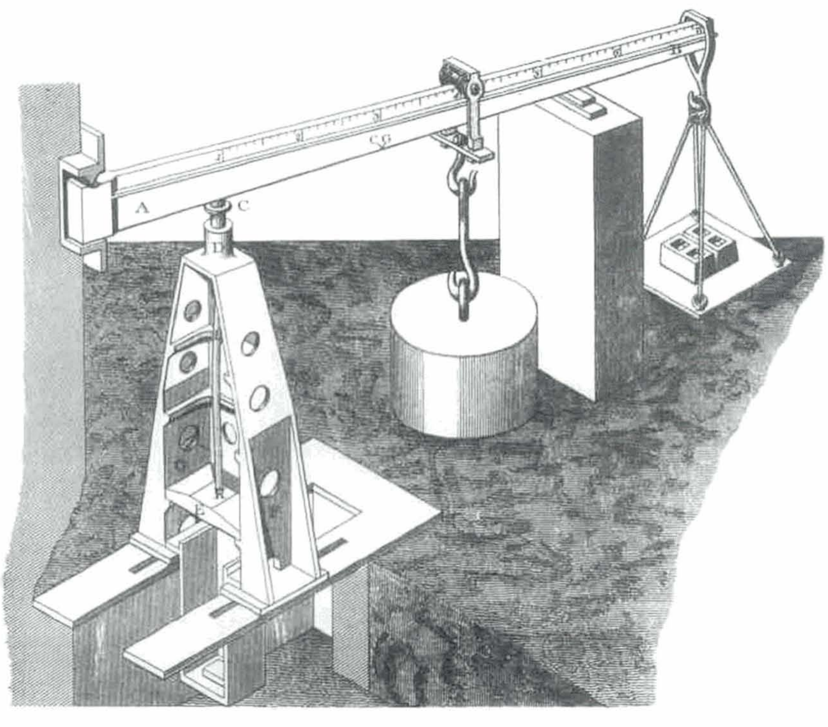


Illustration 189 Eaton Hodgkinson's tests on cast iron pillars [Test arrangement] (Source: Swailes, 2004)

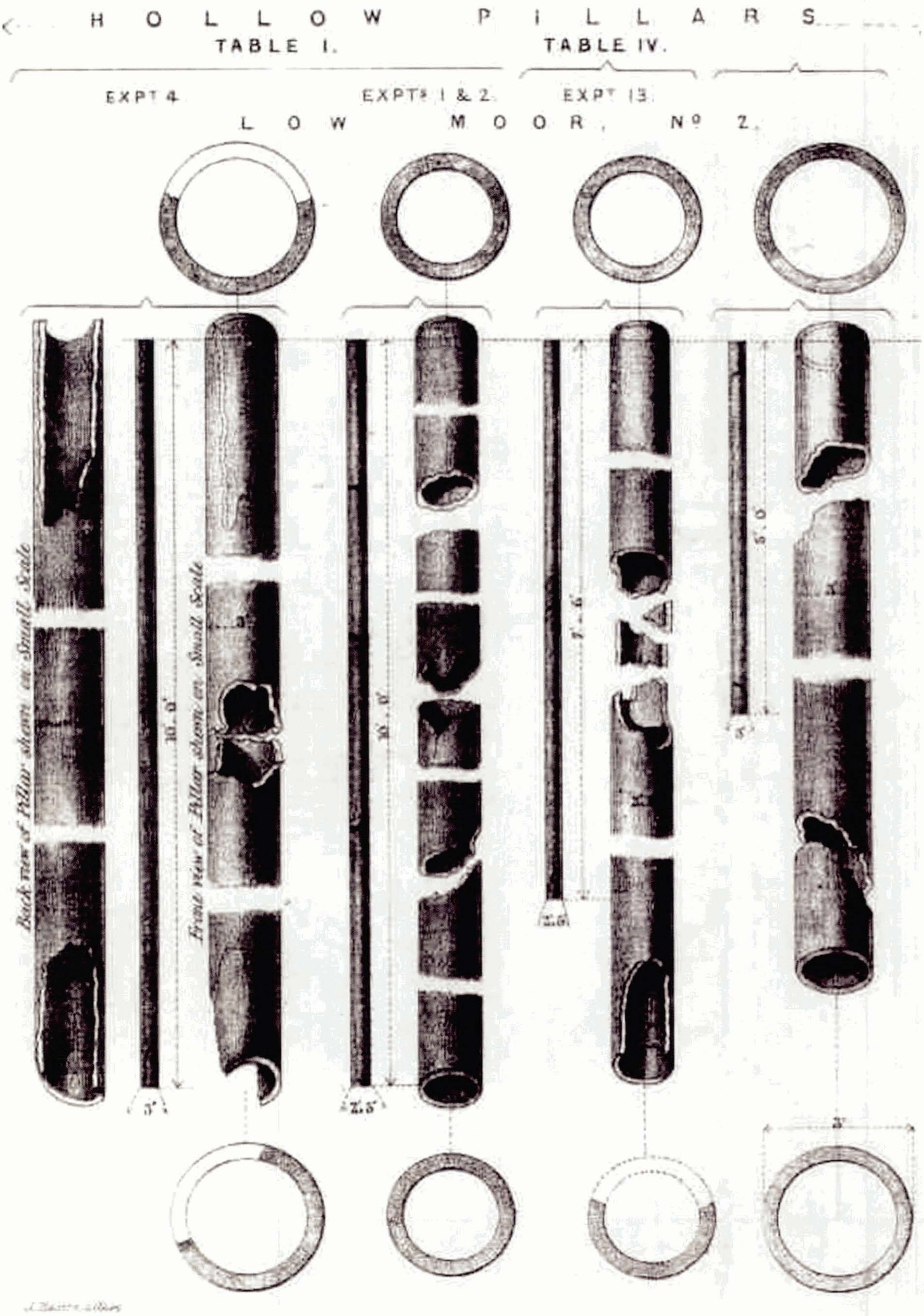


Illustration 190 Eaton Hodgkinson's tests on cast iron pillars. Fractures of hollow pillars (Source: Swailes, 2004)

the USA, and factors of safety for use in assessment were increased (Illustration 196) (Swailes, 1997). It seems very likely that the ripples of alarm crossing the Atlantic Ocean led to the introduction of conservative assessment methods by the London County Council (General Powers) Act, 1909. The LCC Building Act Committee at the time certainly made a study of the American codes (GLC, 1976). Structural framing details of the Darlington Apartments were deficient in that projecting bearings for steel beams resulted in large eccentricities of load on the cast iron columns (Friedman, 1995). Temporary lateral stability bracing was also inadequate.

Reference has been made in Section 6.4.1 to 'historical damage' suffered by cast iron columns. In more recent times, numerous examples of roof collapse due to fracture of a supporting cast iron column by a fork-lift truck have been recorded (Lovejoy, 1988). Small diameter columns in low-rise buildings such as mill weaving sheds are particularly vulnerable. Guidance on minimising the risks has been issued by the Health and Safety Executive (HSE, 1999). The solutions are to remove the powered vehicle hazard, to protect the columns by barriers or suitable encasement, or to provide steel or ductile (SG) cast iron replacements with adequate impact resistance in vulnerable locations.

6.5 Cast iron beams

6.5.1 Details, manufacture and defects

Early in the nineteenth century beams might be cast directly from the blast furnace. Later practice was to re-melt the pig iron in a secondary furnace, or cupola, giving more control over the operation and a better quality end product (Swailes, 1996). The choice of raw materials was sometimes made by an engineer, but for building works was often left to the experience of the ironfounder.

A re-usable wooden replica or pattern of the beam was made, very slightly oversize to allow for shrinkage of the iron on cooling. I-section beams were most often cast with their webs horizontal (Illustrations 197 to 203). The lower part of the mould for large beams would be formed directly in a deep layer of sand in the foundry floor. The upper part of the mould would be made in one, two or three mould boxes, and would normally be air-dried and then fitted in place over the lower part of the mould prior to casting.

A clayey sand mixture was used for moulding, compacted in layers, but not so densely as to prevent the escape of gases generated due to the damp nature of the 'green sand' mould. The 'ventilation' of the mould was an important element of the moulders craft as

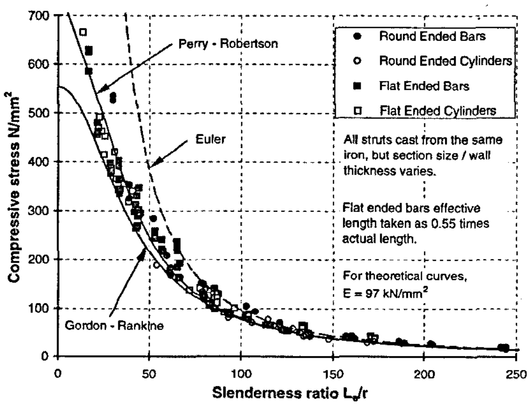


Illustration 191 Experimental and theoretical strut buckling curves (Source: Swailes, 2004)

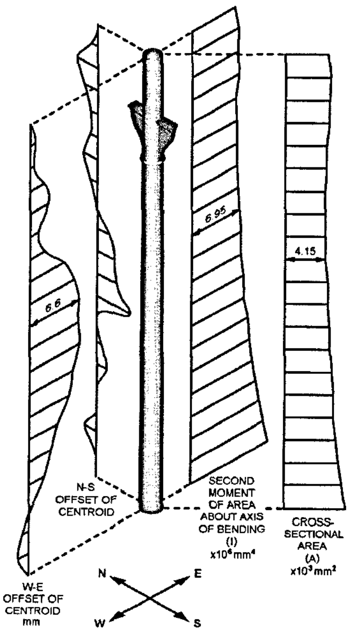


Illustration 192 Typical section property variations for a test column from Stanley Mills (Source: Swailes, 2004)

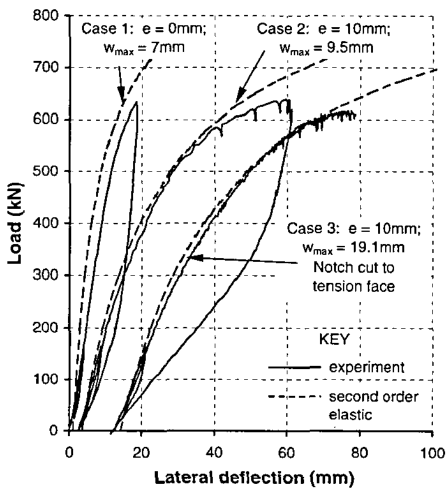


Illustration 193 Test results for Column 1 (Source: Swailes, 2004)

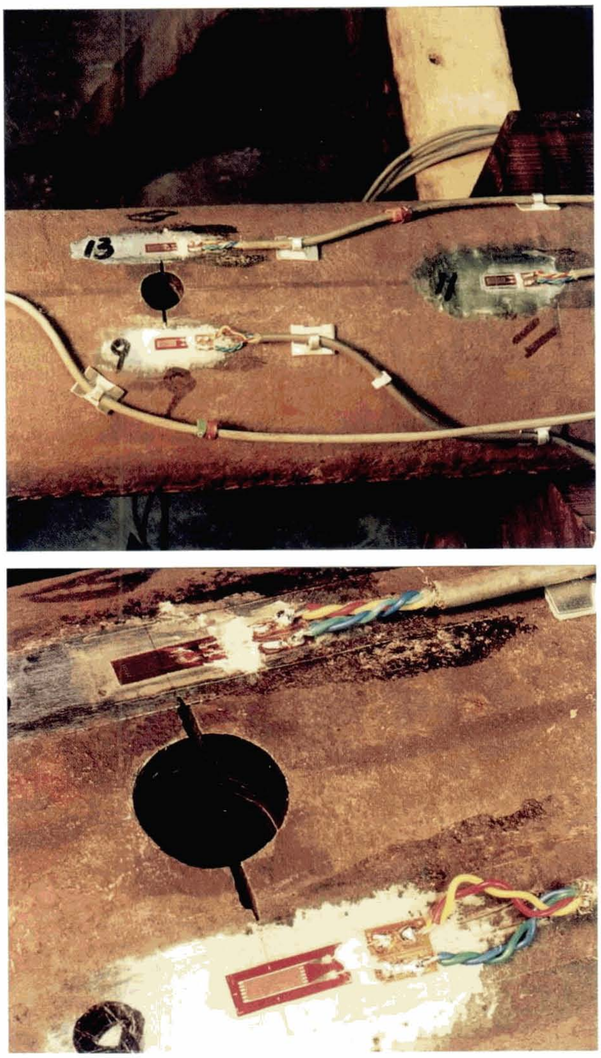


Illustration 194 Details of artificial defects in the convex face of Column 1 (Picture: T. Swailes)

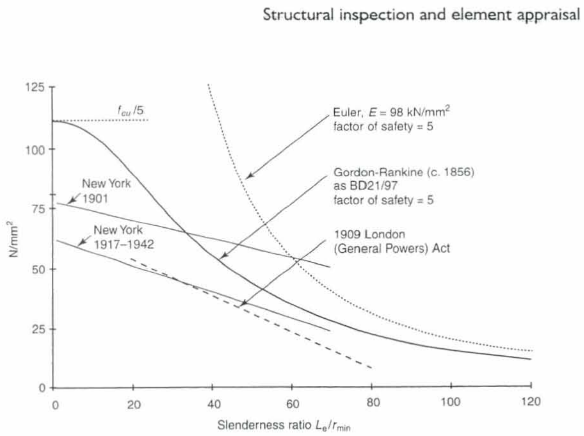


Illustration 196 Historic cast iron column design curves (Source: Swailes and Marsh, 1998)

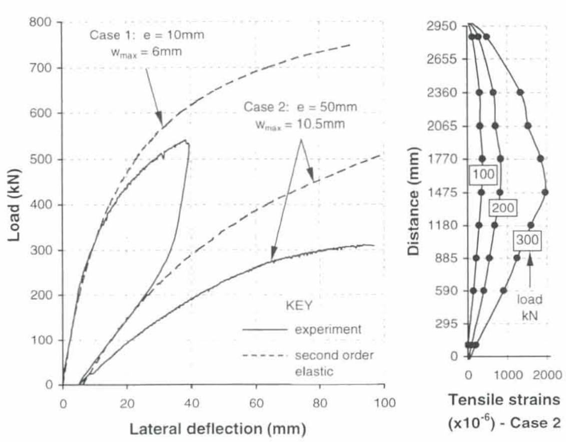


Illustration 195 Test results for Column 2 (Source: Swailes, 2004)

without it excessive blowholes would be the result. For light, decorative castings, a relatively open-textured sharp sand was favoured for its self-venting properties. For structural beams and columns, a closer textured moulding sand was necessary to resist the greater pressures from the molten iron and the effects of intense heat over a longer period. A piece of wire was pushed through the moulding sand at approximately 6" intervals to promote ventilation. Mould finishes varied, with special facing sands used, sometimes coated by brush with a coal dust based 'blacking' that would burn off and result in a smoother surface finish to the casting. Holes in beams, for tie bar fixings for example, were usually formed by the use of separate oven-dried 'core' moulds. Prefabricated iron frames were often very carefully thought out. Beam to column connections depending on relatively sophisticated beam end details that demanded skilled work in the foundry (Illustrations 198 & 199).

The detrimental effects of rapid cooling on the end product were appreciated and heavy castings were sometimes left in the sand for a day or more. Giving evidence after the collapse of a mill in Oldham in 1844, William Fairbairn gave 10 hours as the minimum period for which 'fireproof' beams should remain in the sand after they are cast. However, Joseph Whitworth (of screw thread fame) said that some small foundries removed castings red-hot from the sand, to

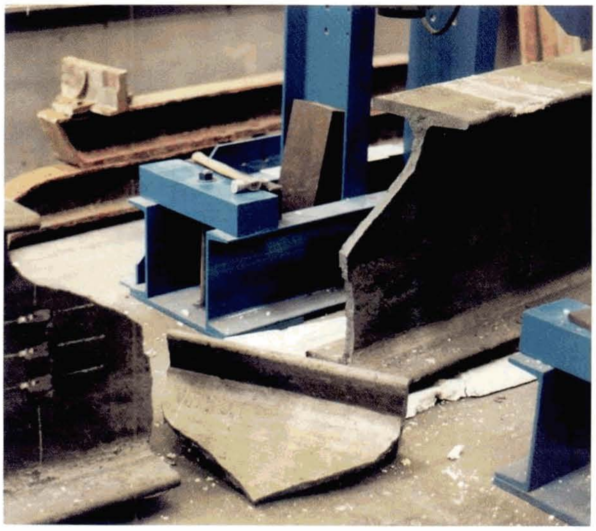


Illustration 197 Large I-section columns from a c. 1855 Engineering Workshop at Chatham Dockyard Fracture after testing in bending, with compression zone wedge (Picture: T. Swailes)

Illustration 198 Havelock Cotton Mill, Manchester (c.1845) Ends of cast iron beams saved for testing (Picture: T. Swailes)

Illustration 199 Havelock Cotton Mill, Manchester (c.1845) Iron framing exposed during demolition in 1995 (Picture: Joe Marsh, UMIST)

save time, space and money (Royal Commission, 1845). Quality control in other aspects of foundry work was equally variable and, unfortunately, a good surface finish is no guarantee of a good beam. A variety of qualitative tests for the soundness of castings were used, a writer in Glasgow Mechanic's Magazine in 1830 recommending that the edge of the casting be tried with a hammer: 'If fragments fly off, and no sensible indentation be made, the iron will be hard and brittle'.

Minor flaws which may be seen in most fractures and sometimes on the surface of a casting have little effect on the static or fatigue strength of a beam, given the relatively low notch sensitivity of the material. Most common are roughly spherical holes that may be 10mm or more in diameter just below the surface of the iron, or breaking the surface as 'blowholes', formed by gas bubbles which rise upwards within the mould. Potentially serious flaws include contamination of the iron by moulding sand, or 'cold joints', produced by an interrupted flow of the molten metal (Illustration 205).

Practice in proof testing beams in an effort to detect serious weakness varied, as did the loads to which beams were proved. In some cases every beam was proof tested to its working load and in other cases only one typical beam was tested to destruction to prove the adequacy of its design.

6.5.2 The evolution of different forms of beam

Cast iron was first introduced as a material for beams in industrial buildings at the end of the eighteenth century because, unlike timber, it is incombustible. The northern part of Houldsworth's cotton mill in Glasgow, now demolished, was one of the earliest 'fireproof' buildings in Scotland, built in 1804-5. Brick arches sprang from the bottom flanges of inverted tee section cast iron beams of 12' 6" span and spaced 8' 6" apart (Illustration 200) (Hay, 1986). Very early cast iron beams tend to have a narrow, parallel sided bottom flange, around 4" wide.

The span of the beams determined the number and spacing of columns across the width of a building but was limited in 'fireproof' construction by the great weight of the floor. However, greater column spacings were needed as cotton mills were designed to accommodate increasingly large spinning mules. By 1825, William Fairbairn was testing inverted tee section beams of around 21' span for use in a Bradford mill (Fairbairn, 1870). In 1827, he provided experimental facilities for fellow Manchester Literary and Philosophical Society member, Eaton Hodgkinson. The collaboration between the two men proved to be a great success, resulting in the 'Hodgkinson Beam' (Hodgkinson, 1831). Surprisingly, the new form of beam was first used in a railway bridge. George Stephenson was a friend of William Fairbairn and obtained from him Hodgkinson beams of almost 25' span for a level girder bridge to carry the Liverpool and Manchester Railway over Water Street in Manchester (Fitzgerald, 1980). By the 1840s the 'Hodgkinson beam', with its small top flange and larger bottom flange, was widely used for railway bridges and preferred in fireproof mill construction. Design for a given span and load was straightforward using the 'Hodgkinson formula'. The cross-section of later cast iron beams very often varies along their length, with the bottom flange becoming slightly narrower towards the supports (Illustrations 201 to 203).

Cast iron beams of large size were used by the architects of many of the great houses, public buildings and palaces of early nineteenth century Georgian England. In such buildings, structural ironwork is generally concealed and the only Scottish examples so far identified date from the Victorian era. Large inverted tee sections were designed by John Nash in the 1820s for use in Buckingham Palace. Most other architects, including Robert Smirke, Jeffrey Wyattville and Charles Barry, left the design and proving of cast iron beams to a structural ironwork subcontractor. The engineer and ironfounder J U Rastrick designed and load tested cast iron beams of unprecedented span for Robert Smirke's British Museum (Slade, 1995). These were a prototype for similar beams used some 20 years later by William Nixon at St. Andrew's University (see Illustration 92). Builders and architects often favoured the 'Tredgold beam', designed according to principles set down by Thomas Tredgold in a 'Practical essay on the strength of cast iron and other metals' first published in 1822. Tredgold beams have top and bottom flanges of the same size. The derivation of Tredgold beam design tables was based on the bending strength of small bars and, for beams, the tables give an inadequate factor of safety against failure (Sutherland, 1980).

6.5.3 Strength and assessment

Twentieth century engineers have been concerned with the assessment of beams in existing construction, rather than with the design of new cast iron beams. In simple terms this involves calculation of the elastic bending stresses in a beam under its working loads and comparison of the tensile stress value with the safe working stress, or the permissible stress, of the material. Design tensile stresses are considered in Section 5.3.3 (b). Only in unusual cases will shear or bearing stresses govern, although the stability of a laterally unsupported web or compression flange is sometimes an issue.

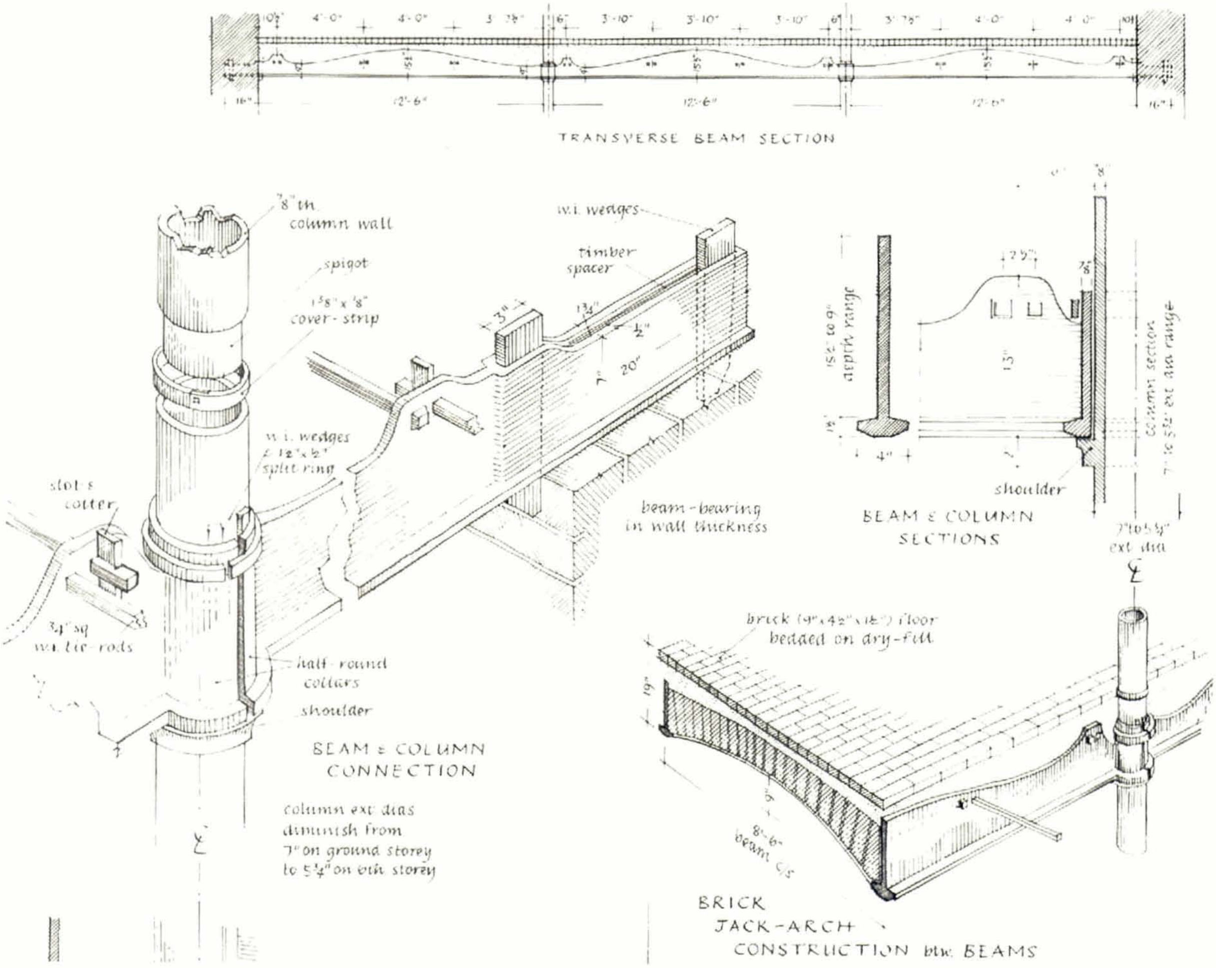


Illustration 200 Houldsworth's Cotton Mill, Glasgow (c.1804) Beam and framing details (Picture: RCAHMS in Hay & Stell, 1986)

Illustration 201 South Mills, Dundee (1864) A Hodgkinson type beam over a partially demolished fireproof basement (Picture: RCAHMS)

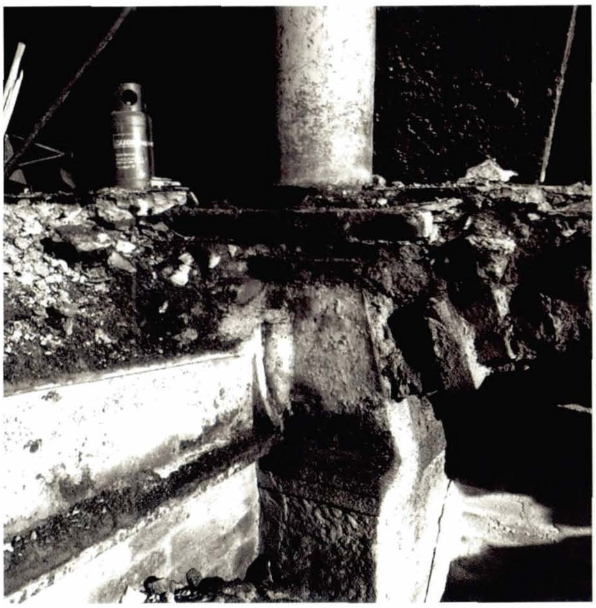


Illustration 202 South Mill, Dundee (1864) A cast iron column on a large cast iron base, also supporting a ground floor beam (Picture: RCAHMS)

Illustration 203 South Mill, Dundee (c.1851, date of this building 1864) A cast iron beam with a hog-backed profile (Picture:RCAHMS)
Note the small bulb-shaped top flange and the dovetail on the beam end, to slot into a recess in the cast iron base of Illustration 32

Between 1935 and 1944 tests were carried out to investigate the ability of cast iron girder highway bridges to carry heavy military vehicles (Chettoe, 1944). Analysis of the then available results of breaking tests on full-size cast iron bridge beams showed that Hodgkinson's formula, derived from tests on small beams, gave an over-estimate of minimum likely strength. A graphical plot of the available test data provided a basis for obtaining a lower bound value for the strength of a cast iron beam (Illustration 204). The average modulus of rupture for bridge beams removed for testing was 8 tons/in^2 (124 N/mm^2) This value was taken as confirmation of the 'wartime' permissible bending tensile stress of 2.5 tons/in^2 (39N/mm^2) in use in the 1940s for the assessment of such bridges.

Tests on complete bridges showed that bridge beams were stiffened considerably by the material encasing them. In estimating live load stresses it was recommended that the section modulus of the beam should be factored by the ratio D/d, where D is the overall depth of the bridge deck and d is the mid-span depth of the beam. A typical value for D/d in a girder bridge is 2, although there is an upper limit for assessment, so the enhancement of strength due to composite action is considerable. In most forms of deck, the effects of a concentrated wheel load were spread across several beams and load distribution coefficients were provided to enable this load-sharing to be taken into account in an assessment. Tests on a bridge by the Transport and Road Research Laboratory in 1991 confirmed that guidance in the Department of Transport standard relating to cast iron girder bridges, largely based on the results of the wartime tests, was reasonable (Daly, 1991). The fatigue strength of cast iron bridges is at present the subject of research by the author.

The BD21 permissible stresses for cast iron are presented in the form of envelopes, both for direct stresses and for shear, in the Steel Construction Institute guide 'Appraisal of existing iron and steel structures' (Bussell, 1997). Reduction in permissible stress is required as the proportion of live load increases. In the SCI publication it is suggested that, with sampling and testing of the cast iron, it may be possible to justify the use of a higher permissible stress than that recommended in BD21. However, it is also noted that, particularly where only a small number of samples can be taken, this approach may not achieve the desired result.

Tensile test results for samples need to be interpreted carefully. There is often a marked difference between the tensile strength of a small sample and 'the modulus of rupture' of the beam from which the sample is taken. This difference may be explained in terms of 'size

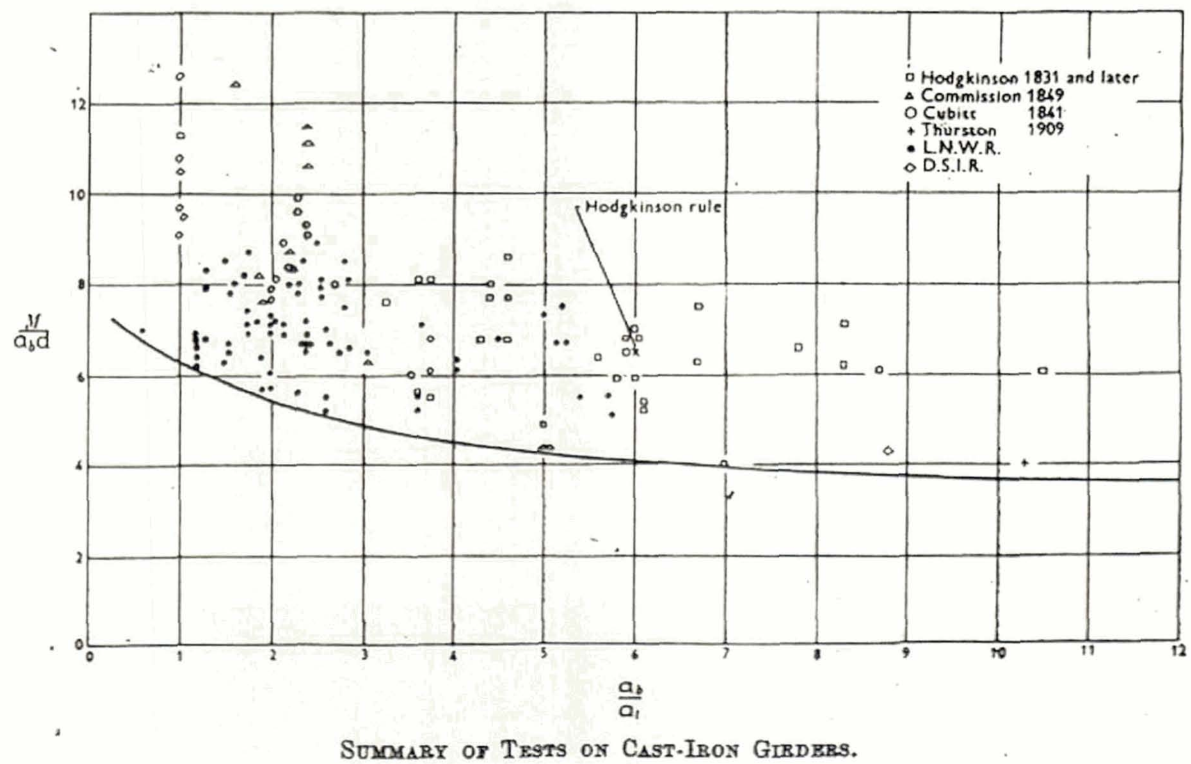


Illustration 204 Bridge beam strength data (Source: Chettoe, 1944) (Picture: Institution of Civil Engineers)

effects', which are a feature of brittle materials (Parmenter, 1996). The results of tests to failure on cast iron beams give a good indication of the range of strengths to be found in nominally identical sections (Swailes, 1998) (Illustration 205). In 1909, at a time when cast iron beams were little used, the London County Council (General Powers) Act introduced a very conservative permissible tensile stress for cast iron of 1.5 tons/in^2 (23 N/mm^2) (GLC, 1976). Reasons for mistrust of cast iron at the start of the twentieth century are considered in 6.4.2. This mistrust was perpetuated by the publication by the British Constructional Steelwork Association of a handbook principally concerned with steelwork in building refurbishment (Bates, 1984). A permissible tensile stress of 18.5N/mm^2 was recommended for the assessment of cast iron beams made before 1900.

No strong arguments have been presented for assessing cast iron beams in buildings against different permissible stresses than are used for bridge beams, and the general use of BD21 stresses is becoming accepted.

A recent collapse has highlighted the need to examine very carefully cast iron beam and brickwork arch construction supporting external paving or roofs. In August 2002, part of an 1838 roof terrace collapsed at Hyde Park Gardens in London (Arnold, 2002). Dead loads had increased considerably since the time of construction with successive resurfacing of the terrace, and water penetration had caused some corrosion of a supporting cast iron beam. Water may also have reduced 'the structural contribution' of the lime concrete fill over the arches. The beam fractured without warning, and it and the supported arches fell into an unoccupied room. The nineteenth century collapse of the roof terrace over the dining room to King's College, London, was in many ways similar to this more recent accident (Swailes, 2003).

T-section cast iron joists from Covent Garden warehouse

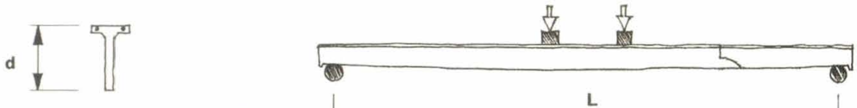
nominally matched specimens (series 1)	test span L (m)	depth at fracture d (m)	section modulus Z_t (mm^3)	'modulus of rupture' f_{bt} (N/mm^2)	tensile strength f_t (N/mm^2)
1	3.49	0.177	1.77E+05	269	
2	3.52	0.178	1.79E+05	258	
3	3.54	0.181	1.90E+05	254	
4	3.65	0.182	2.04E+05	243	
5	3.63	0.181	1.89E+05	237	
6	3.52	0.176	1.78E+05	234	
7A	2.73	0.176	1.76E+05	227	
8	3.54	0.179	1.83E+05	194	
9	3.55	0.178	1.76E+05	194	
10	3.55	0.179	1.77E+05	177	
11	3.66	0.177	1.69E+05	157	
12	3.46	0.178	1.83E+05	136	205
7	3.54	0.164	1.51E+05	66	
averages (excluding specimen 7)			***1.82E+05***	***215***	

The longer broken part of specimen *7* was re-tested as *7A* over a shorter span. The tensile strength value is an average of two tests on 12mm diameter bars cut from the joist flange.

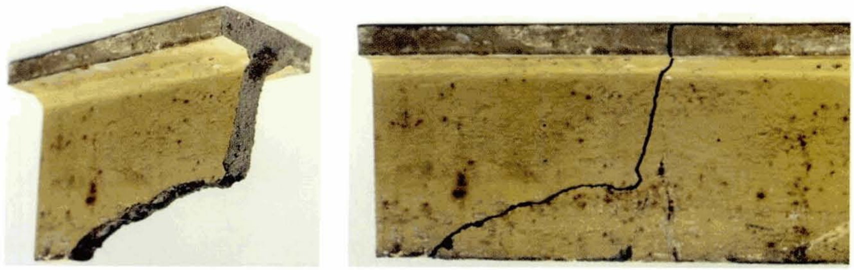
I-section cast iron beams from Havelock Cotton Mill

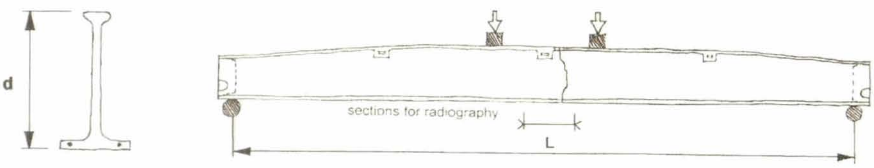
nominally matched specimens (series 2)	test span L (m)	depth at fracture d (m)	section modulus Z_t (mm^3)	'modulus of rupture' f_{bt} (N/mm^2)	tensile strength f_t (N/mm^2)
13	4.66	0.422	2.52E+06	186	
14	4.66	0.419	2.41E+06	173	
15	4.66	0.420	2.47E+06	153	
16	4.00	0.418	2.36E+06	153	186
17	3.99	0.417	2.40E+06	142	175
18	4.66	0.420	2.41E+06	141	
19	4.05	0.424	2.60E+06	131	202
20	4.01	0.422	2.37E+06	130	177
21	4.00	0.420	2.43E+06	130	
22	4.66	0.422	2.45E+06	128	
23	4.03	0.417	2.42E+06	127	158
24	4.66	0.420	2.28E+06	122	183
25	4.66	0.420	2.43E+06	105	198
averages (excl. specimen 25)			***2.43E+06***	***143***	***180***

The tensile strength values are averages of two tests on 16mm diameter bars cut from a piece of the bottom flange of each beam close to the position of the beam fracture.



Joist specimen 7
(note that fractures to all other joists were at or between the load points)





Beam specimen 25

Illustration 205 Cast iron beam and joist test results with selected fracture details (Source: Swailes & Marsh, 1998) (Picture: Thomas Telford Ltd)

7 BUILDING STRUCTURES

7.1 Introduction

This section considers the resistance of iron-framed buildings to loads arising from normal use, to accidental damage, and to the effects of fire. The emphasis is on a qualitative understanding of 'whole structure behaviour', rather than on structural analysis. For example, where and how do wind forces act on a building and how are they transferred through it to the foundations or supports? Lessons from history are also considered.

7.2 Resistance to vertical and lateral loads

7.2.1 Roofs and single storey buildings

Increased dead weight may need to be catered for when a roof covering is renewed or refurbished. Thermal insulation was not important in most buildings with iron roofs and simple coverings were perfectly adequate. A variety of coverings of different weights and with different forms of supporting structure were used in the nineteenth century.

The resistance of iron framed roofs to wind forces may be difficult to prove by structural calculations, although adequacy on the basis of past performance may not be in doubt. Appreciation of the effect of wind on iron roofs by their designers did not include an understanding of uplift effects. The effect of the wind was generally believed to be a downward pressure, normal to the roof slope (Unwin, 1869). Roof supports were often not anchored down to the structure below. Tying down to prevent wind uplift and allowance for stress reversal in roof elements may be necessary if roof dead loads are reduced.

Following Thomas Tredgold's advice, practice for major roofs designed by engineers after the mid-1820s had been to allow a vertical load of 35 lbs/ft^2 (1.68 kN/m^2), with another 5 lbs/ft^2 (0.24 kN/m^2) for snow. Trial ribs for Richard Turner's Liverpool Lime Street roof and Fox, Henderson & Co.'s Birmingham New Street Station roof were test loaded uniformly with 40 lbs/ft^2 (1.92 kN/m^2) and also asymmetrically, with the test load applied to one half only. The roof to the Bricklayers Arms Railway Station was similarly tested, but fell as the result of accidental damage to a supporting column rather than as the result of overloading (G. Mitchell, 2001). When a storm destroyed the open platform roof to the Manchester Exhibition Railway Station in 1857, a wind pressure of 33 lbs/ft^2 (1.58 kN/m^2) was recorded at Greenwich Observatory in London.

The original Haymarket Station train shed was moved from Edinburgh to a more exposed site at Bo'ness. Additional steel cantilever columns placed beside the cast iron columns to the one side of the building cater for the stronger side winds. For wind blowing end-on to the shed, additional steel bracing members were provided both in the roof plane and between the end bay columns to the sides (Illustrations 206 and 207).

Dockyard transit sheds similar in cross-section to the Haymarket Railway Station train shed were probably less vulnerable to wind damage as their doors could be closed during severe storms. Structural engineering calculations may indicate that such structures have inadequate resistance to crosswinds, contrary to the evidence of satisfactory performance over many years. However, where refurbishment provides an opportunity to introduce additional bracing in a discreet manner, it may be acceptable (Illustration 208).

The Linthouse Engine Shop, now at the Irvine Maritime Museum, is well thought out in structural terms. Massive cast iron I-section stanchions with large bases are a characteristic feature of this type of building. They support heavy loads from overhead travelling cranes and also provide lateral stability in the plane of the structural framing (Illustrations 209 and 210). Buildings that followed the pattern established for the Great Exhibition of 1851 also have a central hall, but with two-storey galleried side aisles. Knee braces are used extensively in the framing of Glasgow's Old Fruitmarket to stiffen the beam-column joints in both the transverse and longitudinal directions (see Illustrations 13 and 14). Where stability is provided by portal frame action, avoiding diagonal cross-bracing, realistic modelling of the joints for assessment by structural calculation is likely to be rather difficult.

In the light, curvilinear forms of iron-framed conservatories and glasshouses, arch and dome forms predominate, with various means adopted to prevent spreading at the eaves. The simplest form is a Gothic arch. With the apex unsupported, under vertical loads there will be an outward thrust at the feet of the glazing

Illustration 206 Haymarket Station Train Shed, Bo'ness Heritage Area, Falkirk (1840) Cantilever steel columns attached to the existing frame at eaves level cater for higher side wind forces than in Edinburgh (Picture: T. Swailes)

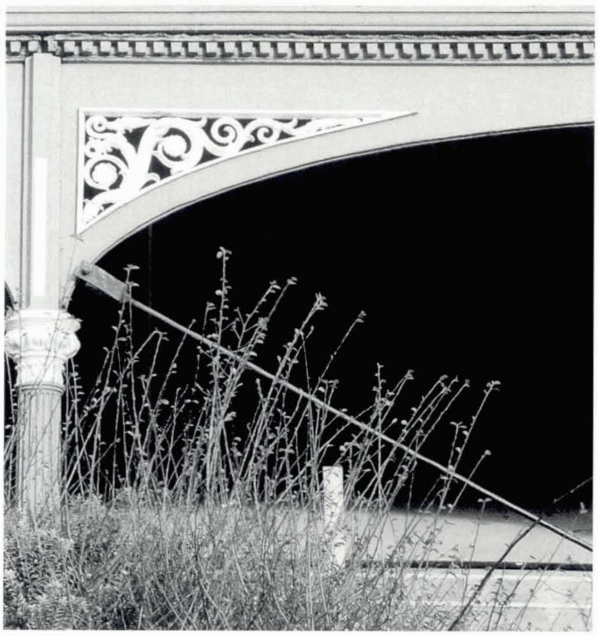


Illustration 207 Haymarket Station Train Shed, Bo'ness Heritage Area, Falkirk (1840) Diagonal bracing to cater for higher longitudinal wind forces (Picture: T. Swailes)

bars or astragals. To some extent the tendency to spread at the eaves may be reduced by the in-plane stiffness of the glazed upper roof slope, with the glazing bars and glazing acting compositely as a plate or stiff sheet. When adequate support is provided at the apex, as in the conservatory at Skelmorlie Castle, the tendency to spread is reduced (Illustrations 211 to 213).

A simpler case still is a half-arch or lean-to conservatory, built against a house or garden wall. A structural appraisal in such a case must also include the building or wall on which the conservatory depends, particularly if the conservatory is to be removed, perhaps with a view to permanent relocation. Under different circumstances, a lean-to might either act beneficially as a prop to a supporting wall or detrimentally by tending to push it over (Illustrations 214 to 216).

Eaves spread may be resisted by tying or trussing, though such arrangements may sometimes appear to be more decorative than structurally efficient. A good example is the passage linking the Kingsknowe Hotel to its conservatory (Illustrations 217 to 220). Domes usually have a perimeter tie or ring beam that prevents eaves spread. Bar or angle iron purlins, supported on principal ribs, may serve as ring ties at higher level. The main dome to Glasgow's Kibble Palace has a series of concentrically placed tie bars between the glazing bars, up the roof slope (see Illustrations 143 and 153). Lateral stability may be enhanced in rather complex ways by abutting structures or decorative features (Illustrations 221 and 222).

Diagonal or cross bracing, of the type used in the lightweight roofs and side bays of modern lightweight steel framed buildings, is rare in traditional conservatories. Instead, forces due to wind pressures are transferred to supports in a complex way through

Illustration 208 Dockyard Transit Shed, Victoria Dock, Dundee (1874) Braced iron frames are visible at intervals along the length of the building. They support a horizontal structural steelwork wind girder at ceiling level, providing a calculable level of safety.
(Picture: Mark Watson, Historic Scotland)

Illustration 209 Linthouse Marine Engine Works, Scottish Maritime Museum, Irvine (1872)
Internal view in 1990, prior to relocation.
Relocated from Alexander Stephen's yard on the Clyde in the early 1990s. Through portal frame type action, side aisles help the tall structure withstand cross winds. Occasional column bays are cross-braced in the longitudinal direction. These braced bays transfer wind forces normal to the gables to foundation level, as the I-section stanchions would be unable to do so as cantilevers bending about their weaker axis. (Source: The Scottish Maritime Museum)

Illustration 210 Linthouse Marine Engine Works, Scottish Maritime Museum, Irvine (1872) Cast iron stanchion detail (Picture: T. Swailes)

the in-plane resistance of the glazed surfaces. The glass should be removed from a large conservatory which is out of use or becoming derelict, where falling glass is a danger to passers-by. All glass removed should be kept safe until such time as it can be re-used. Temporary bracing may be needed to ensure the stability of the bare iron frame. A structure weakened by partial removal or loss of glazing can offer considerable resistance to the wind and be susceptible to storm damage. (Illustration 223).

7.2.2 Multi-storey buildings

The modern steel framed office building is a descendant of the multi-storey iron framed industrial buildings of the late eighteenth century. In a simple steel framed building, vertical and lateral forces due to self-weight, imposed and wind loads are transferred from the roof, floors and external cladding to an independent steel frame. Vertical loads pass from the beams to the columns and then down to the foundations. A bracing system resists lateral loads and also provides stability by holding in position the ends of the main framing members. The bracing may be either a system of steel diagonal members or cross ties, or masonry or concrete walls and shafts (Illustration 224).

Wind loads acting on the external faces of a steel framed building are generally transferred to the bracing system via the floors, which act as stiff plates or diaphragms loaded in their plane. In buildings of traditional construction with timber floors, diaphragm action depends to a large extent on the floor covering. The connections of the floors to the façade and bracing walls are also important. A rare example of a building with diagonal bracing in the floors is Gardner's furniture store in Jamaica Street, Glasgow, built in 1855-6 (Illustration 225). On plan, the building is approximately a rectangle with glazed and iron-framed elevations to two adjacent sides. Timber floor joists are supported on a combination of cast iron beams and 'McConnel patent beams' (see Illustration 90 and section 3.2.5). Diagonal bracing within the floor depth takes the form of a further series of McConnel beams, restraining the iron framed façades and fixed to the interior columns with wrought iron straps. The floors of this building carry loads in a complex way and any calculations for the McConnel beams without some form of confirmatory load testing would be very speculative.

There are differences in the form of multi-storey textile mills and warehouses. To admit natural light to work by, the mills of the mid-nineteenth century are often quite narrow, with large windows between substantial piers of brickwork or stone masonry. In comparison, warehouses tend to be wider with fairly low ceilings

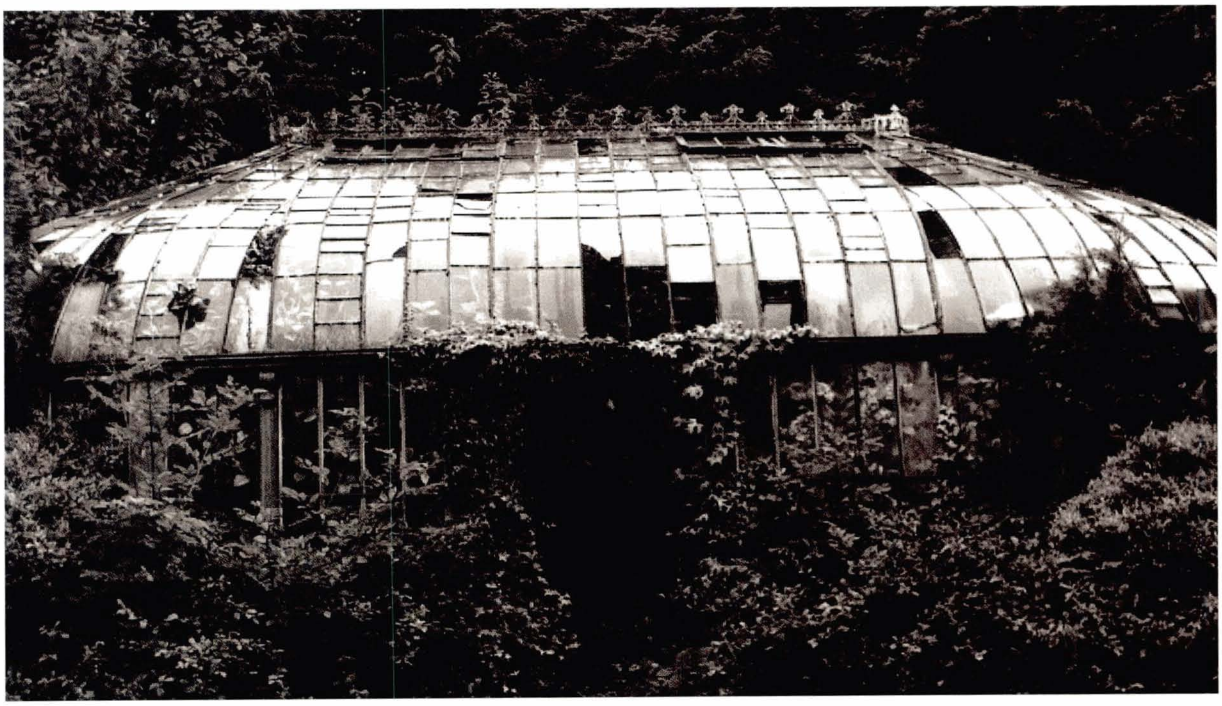


Illustration 211 Skelmorlie Castle, Largs: garden conservatory (c. 1860) External view (front) (Picture: T. Swailes)

Illustration 212 Skelmorlie Castle, Largs: garden conservatory (c. 1860). External view: fine cast iron detailing of the rounded ends (Picture: T. Swailes)

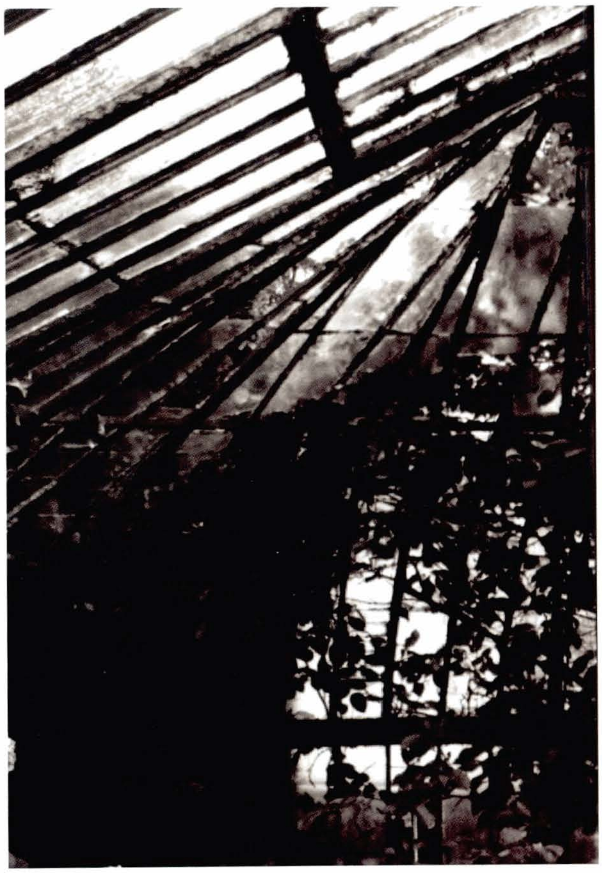


Illustration 213 Skelmorlie Castle, Largs: garden conservatory (c. 1860) The ridge is supported at each end by a cast iron column (Picture: T. Swailes)

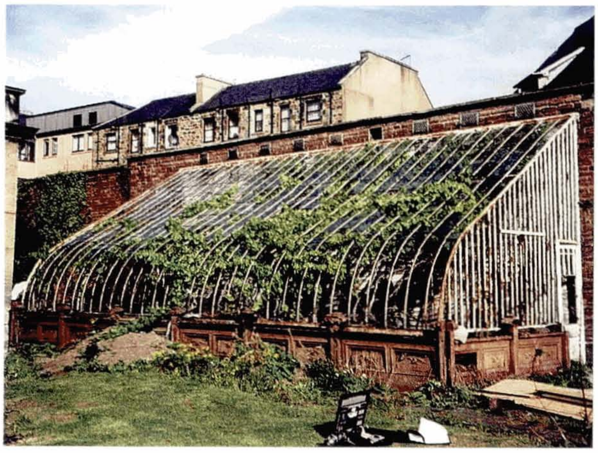


Illustration 214 Fairfield House conservatory, Dalkeith (c.1835) General view, prior to restoration (Picture: Heritage Engineering, The Industrial Heritage Company Ltd.)

Illustration 215 Fairfield House conservatory, Dalkeith (c.1835) Ironwork detail, prior to restoration (Picture: Heritage Engineering, The Industrial Heritage Company Ltd)

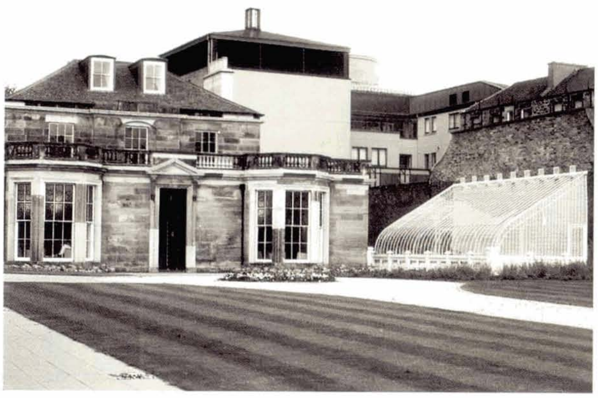


Illustration 216 Fairfield House conservatory, Dalkeith (c.1835) After restoration (Picture: T. Swailes)

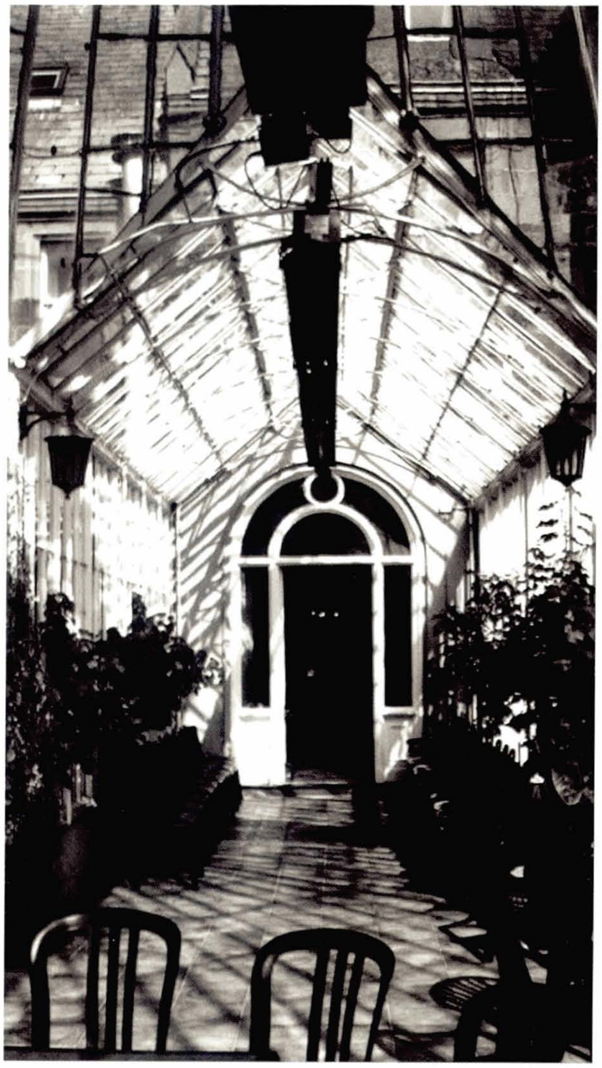


Illustration 217 Kingsknowe Hotel, Galashiels (1868): Conservatory Link passage to the hotel (Picture: T. Swailes)

and stronger floors. Floor beams usually bear in walls or piers on a stone pad, even where the supporting masonry is brickwork. Particularly in cast iron framed mills, the beams are normally well built in to the external wall piers and tests have shown that this gives a 'partially fixed' end condition. (Swailes, 1988)

Cast iron columns generally provide internal support to floors. Timber beams may be continuous over or 'through' columns, but scarf joints (with limited moment capacity) between lengths of timber may prevent the achievement of full structural continuity.

It seems likely that two types of structural action combine to resist cross winds blowing on a tall, long and narrow iron framed textile mill building. Often there will be no internal walls to act as bracing. Firstly, a proportion of the load due to wind pressures on the long elevations of the building may be transferred by the floors spanning horizontally as stiff plates between

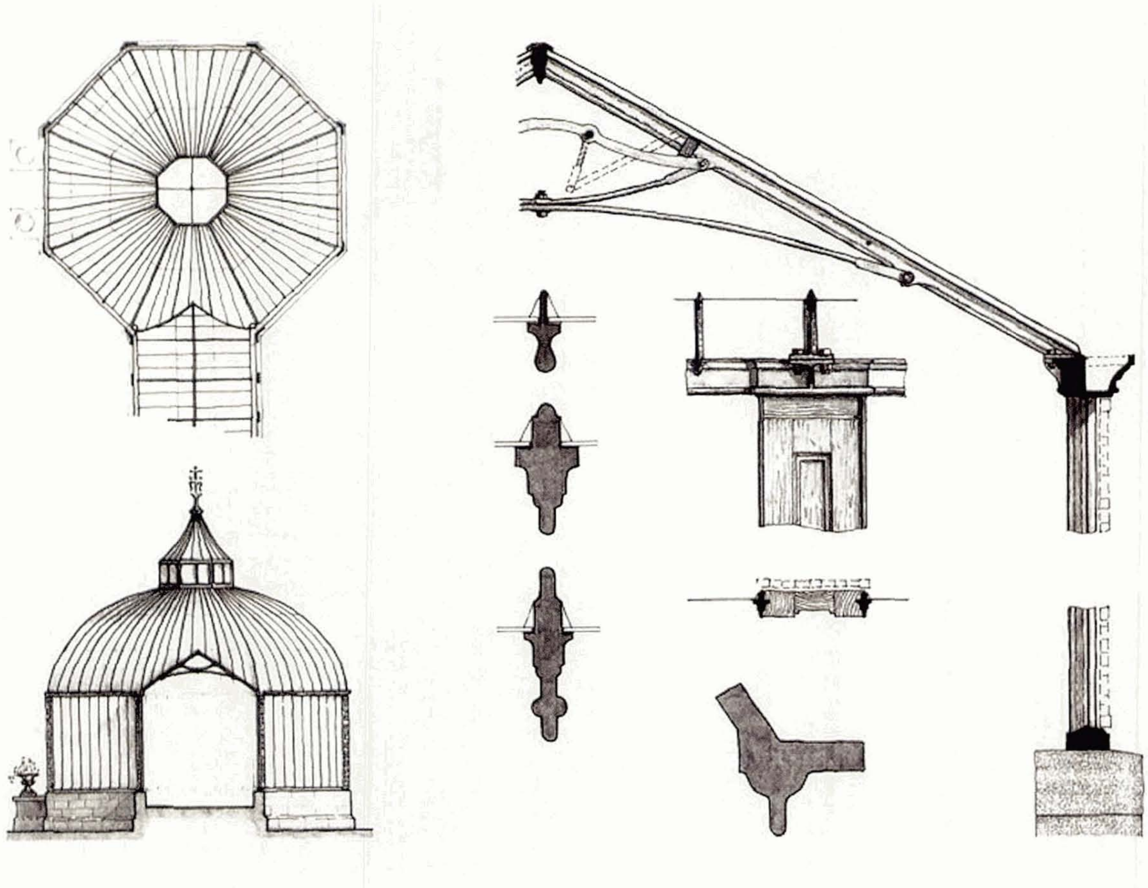


Illustration 218 Kingsknowe Hotel, Galashiels (1868): Conservatory Ironwork details (Picture: T. Swailes)

the gable walls. The remainder of the load on each bay width may be carried by 'frame action', with the heavy masonry piers between the windows acting as the outer column members of a transverse frame, together with the floor beams and the internal cast iron columns. That frame action is a reality has been proven by site tests.

7.3 Resistance to disproportionate collapse

7.3.1 Background

'Failures in construction often teach more than successes, inasmuch as experiences, dearly bought, leave an indelible impression, and open our eyes to circumstances not before perceived' (Nash, 1867).

A distinction was drawn between stability and robustness in section 4.3. A specified level of robustness (or resistance to 'disproportionate collapse') became a requirement in the construction of new buildings of 5 storeys or more after the partial collapse of a 23-storey block of flats at Ronan Point in London (Griffiths, 1968). An unexceptional gas explosion in the kitchen of an eighteenth floor corner flat blew out an external load-bearing flank wall, the structure comprising prefabricated concrete floor and wall panels on the Danish Larsen Nielsen system. The flank walls and floors above collapsed in turn, and the weight and impact of the falling concrete panels caused the corner of the building to collapse down to first floor level. Four people were killed.

Mandatory Standard 1.2 of the Scottish Building Standards states: 'every building must be designed and constructed in such a way that in the event of damage occurring to any part of the structure of the building the extent of any resultant collapse will not be disproportionate to the original cause'. For requirements relating to the provision of ties and design against misuse or accident, reference is made in The Building Technical Handbooks Technical Standards to British Standards BS8110 (reinforced, prestressed or plain concrete), BS5950 (structural steelwork) and BS5628 (structural masonry).

Formerly, Building Regulations also required that resistance to disproportionate collapse be considered for roof or other structures spanning 9m or more over public spaces. The safety of a large roof under which a large crowd of people may gather is clearly more critical than for a construction of more modest scale.

Illustration 219 Kingsknowe Hotel, Galashiels (1868): Conservatory External view (Picture: T. Swailes)

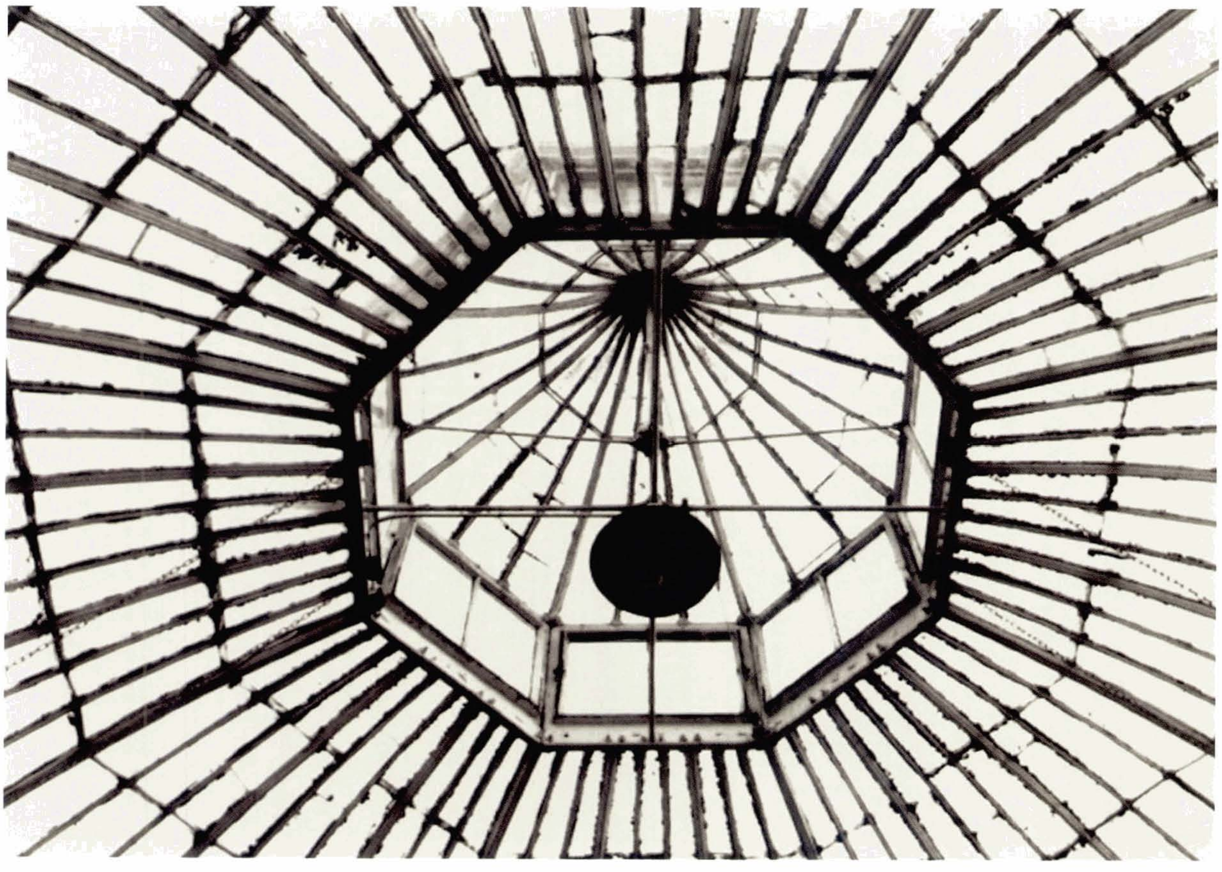


Illustration 220 Kingsknowe Hotel, Galashiels (1868): Conservatory Internal view of the dome (Picture: T. Swailes)

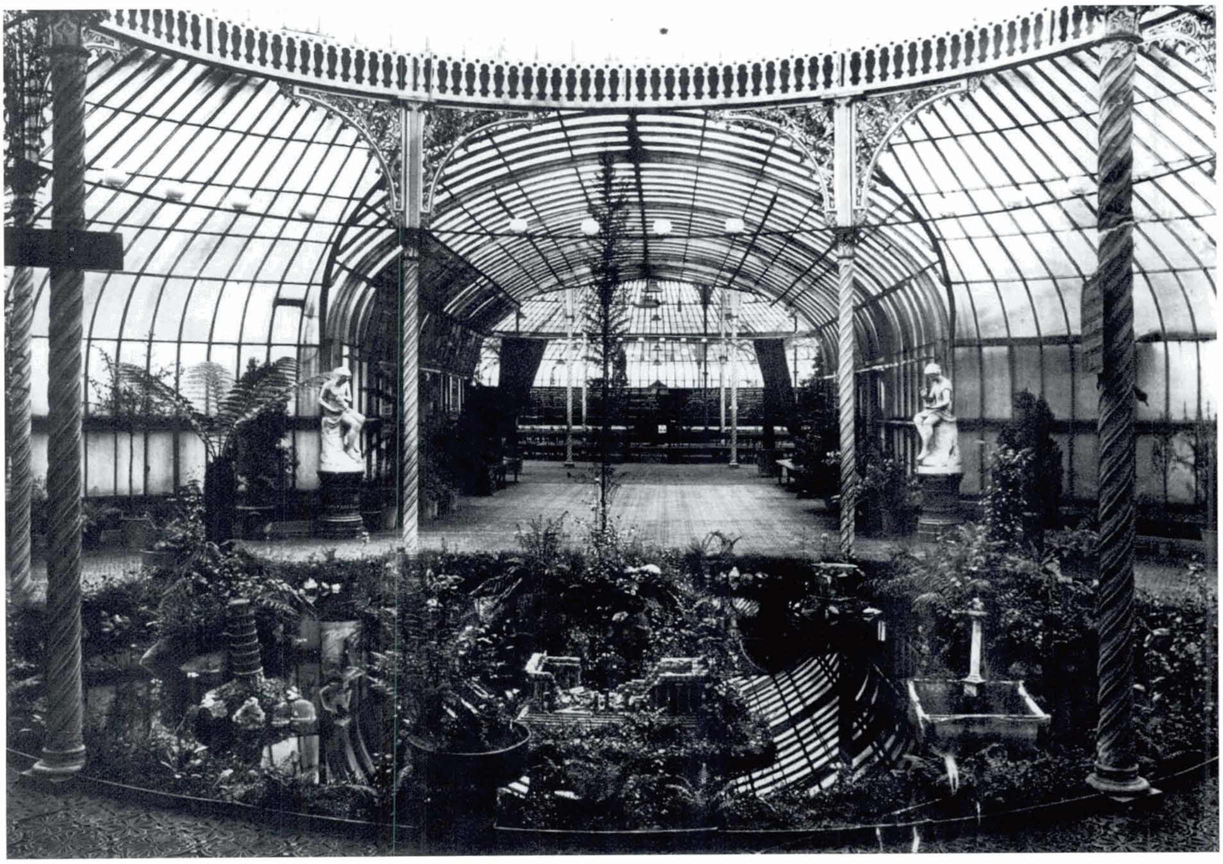


Illustration 221 The Kibble Palace, The Botanic Gardens, Glasgow (1873)

Illustration 222 The Kibble Palace, The Botanic Gardens, Glasgow (1873) (Picture: David Mitchell, Historic Scotland)
Cast iron columns, with standard braced support a ring beam beneath the clerestorey

7.3.2 *Multi-storey buildings*

The disproportionate collapse requirements of the Building Regulations may not at present need to be considered for every mill, factory, or warehouse refurbishment project. One of the deciding factors is the category of use for which a building is to be adapted. The local authority building control authority should be consulted to determine the extent to which the requirements of the Technical Standards apply in any particular case. Multi-storey buildings of traditional construction have a good safety record and, when cared for properly, they provide safe places in which to live and work. Often when robustness is an issue, structural calculations that are based upon codes of practice and other authoritative guidance applicable to modern structures will be inappropriate. In accordance with the advice given in the British Standard guide to the principles of the conservation of historic buildings, 'it will be necessary to follow professional experience and judgement, on the basis of what has been proved to work' (BS 7913, 1988). Robustness can be improved, for example, by the provision of better horizontal tying within the floors of a building or by the protection of vertical supports that may be vulnerable to damage. The improvement achieved by such measures may not be quantifiable, but can often be gained at relatively little cost during a refurbishment project.

The seriousness of a structural failure increases with the size of the building, as demonstrated in a shocking manner by the progressive collapse in September 2001 of the twin World Trade Center towers in New York. Collapses among the first generation of American multi-storey buildings led to a distrust of cast iron columns, which with hindsight was rather misplaced. In 1860, a five-storey cotton mill in Massachusetts collapsed while 700 people were at work. The building was not of fireproof construction and a fire started in the ruins, resulting in 88 deaths (Wermiel, 1995). Although the finger of blame was pointed at 'outrageously defective' cast iron columns, the collapse was due to a combination of several factors. In 1904 a high-rise New York apartment block collapsed when construction reached the eleventh storey, killing 25 workers. Steel beams were supported by cast iron columns via eccentric brackets, with construction bracing not provided (Friedman, 1995).

All buildings are at their most vulnerable when in an incomplete state, either during construction or refurbishment, or as the result of damage caused by fire, accident, or neglect. Iron-framed 'fireproof' buildings with cast iron beam and brick arch floors have been prone to catastrophic collapse under these circumstances. Examination of brief details of some recorded accidents, including some Scottish examples, is instructive. The large number of fatalities in

Illustration 223 Tollcross Winter Garden, Tollcross Park, Glasgow (1858)
The derelict structure before renovation, with glazing removed and security fencing in place to discourage unauthorised access to the building. (Picture: T. Swailes)

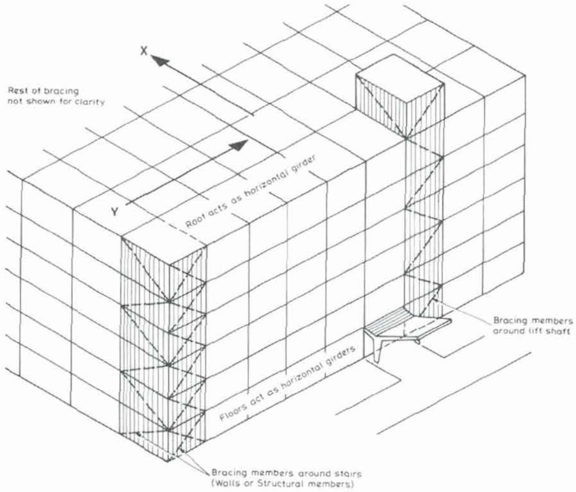


Illustration 224 Building bracing systems (Source: IStructE, 1988) (Picture: The Institution of Structural Engineers)

nineteenth century mill collapses was a consequence of the practice of occupying lower floors before the construction of the floors above was complete. Very many buildings of this kind have been adapted with great success for new uses, but their refurbishment must always be carried out with appropriate skill and care, under the direction of a suitably qualified and experienced engineer.

Brickwork floor arches are very strong if undisturbed, but very heavy. The collapse of an upper floor arch onto to the floor below would be quite likely to cause the collapse of that floor in turn, possibly through failure of the supporting beams. Arches are sensitive to lateral movement of their supports and to loss of mortar from the brickwork joints. The comparative superiority of 'filler joist' floors was demonstrated recently in the partial collapse of a fireproof former textile mill in Hull. Several arched lower floor bays had been replaced with filler joist construction many years prior to the collapse. None of the replacement floor bays failed, the filler joist floor proving able to support the weight of three collapsed brickwork arch floors from above.

In the mid-1990s, a six-storey fireproof textile mill dating from 1865-66 was refurbished to accommodate the University of Huddersfield's School of Computing and Mathematics (Bussell, 1998). The floors, with brick arches supported on cast iron beams, were strengthened by replacing the original covering to the arches with a continuous slab of lightweight concrete, reinforced with steel mesh (Illustration 226).

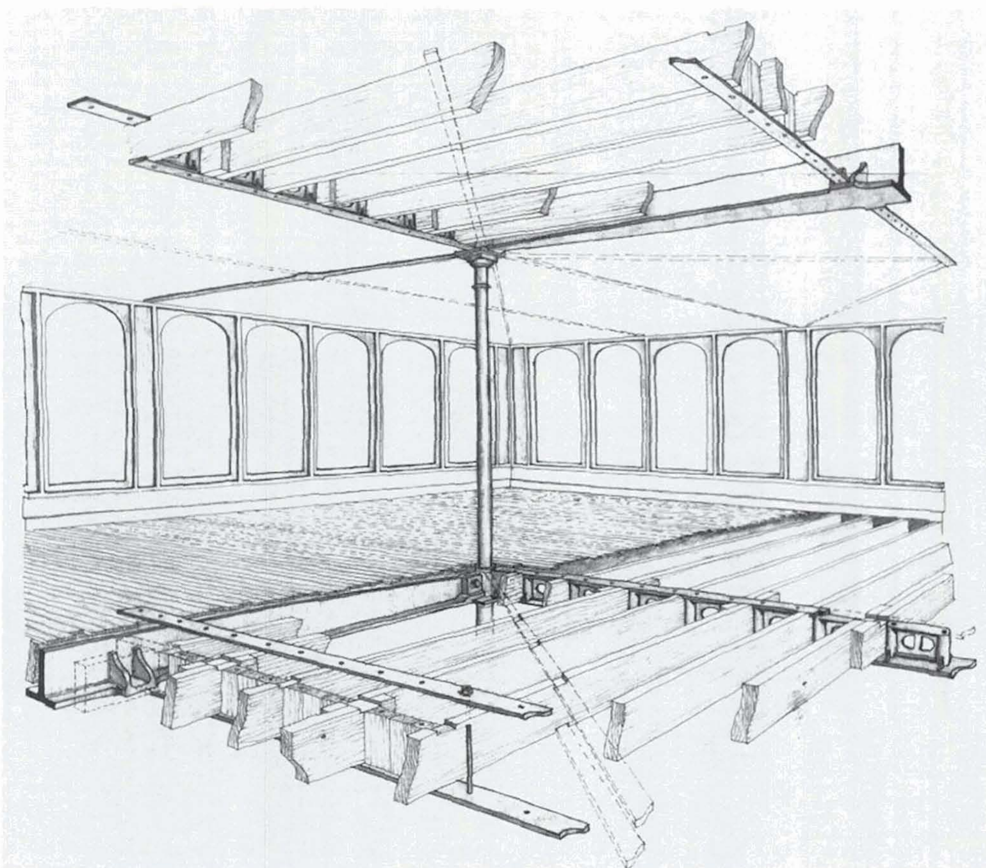
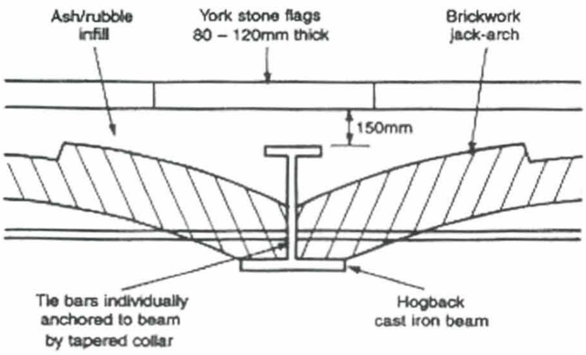


Illustration 225 A. Gardner & Sons Furniture Warehouse, Jamaica Street, Glasgow (1855) (Picture: T. Swailes) Interior view, showing the structure beneath the floorboards. In some 'secondary' McConnel beams, web blocks of timber (with face grain vertical) were used instead of cast iron, this variant being provided for in the patent.

Cast iron columns in multi-storey buildings of all types are nearly always discontinuous, with simple spigot joints at each floor level. The failure of a lower storey column or its foundation is therefore likely to cause quite extensive collapse unless the floors are capable of bridging over the lost support. In 1995, a test was carried out to investigate the effect of the removal of a basement level column in a mid-nineteenth century fireproof cotton mill in Manchester (Swailes, 1997). Although bridging action within the floors was found to be considerable, it was not enough to compensate for the removal of the column. One solution is to provide a lightweight concrete topping to the arches, increasing the effective structural depth of the floor so that locally it can arch over two bays without intermediate support (Swailes, 1998). Deep, stiff floors of this type are relatively brittle compression structures, lacking the flexibility and ductility of modern steel and reinforced concrete floors and frames that enables bridging by catenary action.

Where bridging over a lost supporting element is not possible, that element may need to be protected or



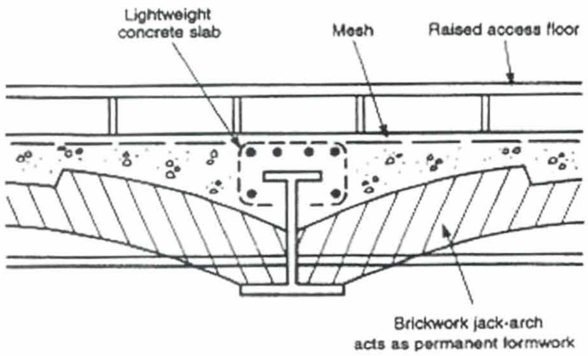


Illustration 226 Firth Street Mill, Huddersfield, England (1865-6) Sections through the floor (a) as found (b) after strengthening. Reinforcing bars were resin-anchored into the supporting external stone walls before the concrete was placed to enhance the hogging moment resistance at the built-in beam ends. These 'invisible' strengthening works also added to the robustness of the building, effectively tying it together horizontally at each floor level in the longitudinal and transverse directions. (Source: Bussell and Robinson, 1998) (Picture: The Structural Engineer)

Illustration 227 Weensland Mill, Hawick (1850) After partial demolition of the remains of the burnt out mill, a masonry wall bridges over two fallen supporting columns (Picture: T. Swailes)

strengthened. For example, a vulnerable column in a ground floor level car park might either be protected by crash barriers, or encased in reinforced concrete to provide impact resistance. Masonry walls do have a remarkable ability to arch over lost vertical supports (Illustration 227).

7.3.3 Roofs

One-way spanning iron roofs lack redundancy and the consequences of the failure of a support or of a critical element to a long span are likely to be serious. Prior to the introduction of raised platforms at stations, numerous roof collapses were caused by the loss of a supporting cast iron column, struck by de-railed rolling stock (Mitchell, 2001). The vulnerability of cast iron columns to impact damage is considered in section 6.4.1.

A tragic progressive collapse occurred at Charing Cross Station in 1905. During re-glazing of the 40 year old roof, several roof bays and the gable screen fell. This caused a wall to fall on adjacent property, killing 6 people. The accident was blamed on a defective threaded end to one of the principal wrought iron tie bars (Jackson, 1969). Some accidents resulted from misuse of a building. Twelve people died in 1828 when the cast iron roof to the Brunswick Theatre collapsed during a rehearsal (Mechanic's Magazine, 1828). It was overloaded with heavy machinery and the supporting walls were considered too slender.

7.4 Floor systems and their structural behaviour

7.4.1 Arch and beam floors

Where cast iron beams support brick arches in a fireproof floor, the dead load stresses are considerable. Even allowing for end fixity, the load capacity of the beams will be limited due to the low tensile strength of the cast iron. The effective beam stiffness (EI) obtained by considering the brickwork and cast iron to act compositely is about 1.5 times that for the cast iron beam alone. However, because most of the arch material is above the cast iron beam neutral axis, the increase in strength is negligible.

Strengthening may be achieved by removal of the material over the arches and replacement with a lightweight reinforced concrete topping to obtain a composite concrete and cast iron beam (Rhodes, 1987). The Institution of Civil Engineers Design and Practice Guide 'Structural appraisal of iron framed textile mills' includes a worked example (Swailes, 1998)

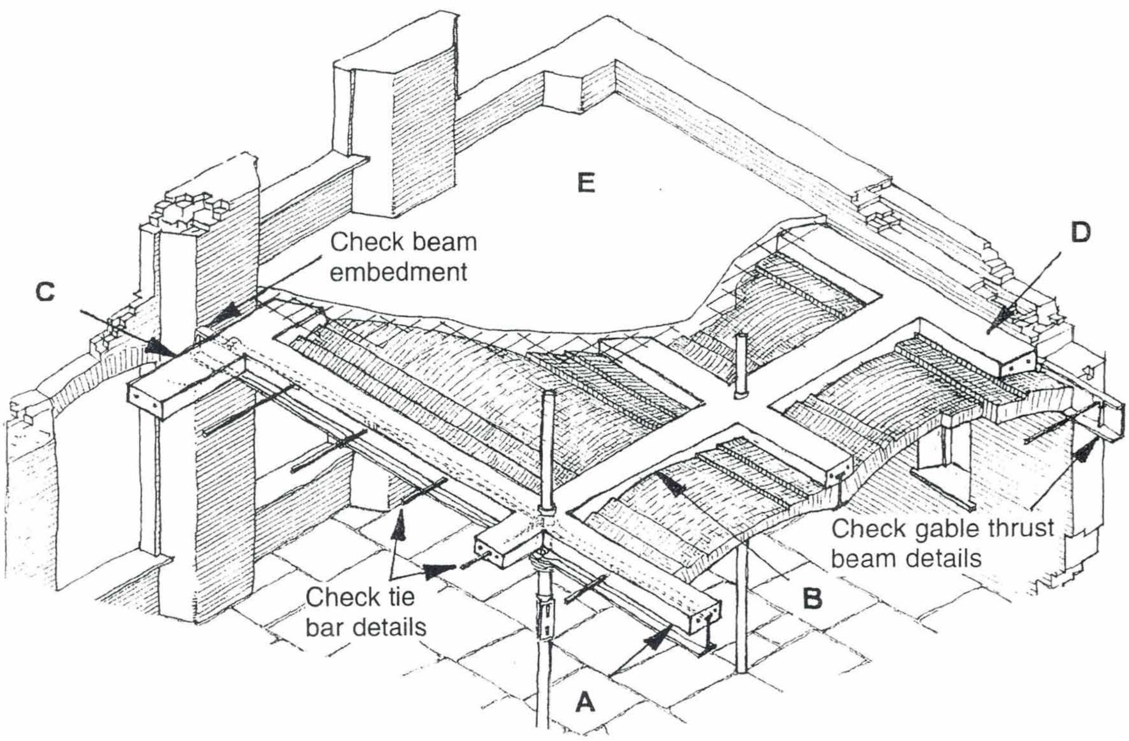


Illustration 228 Strengthening solutions for fireproof textile mills (Source: Swailes & Marsh, 1998) (Picture: Thomas Telford Ltd)

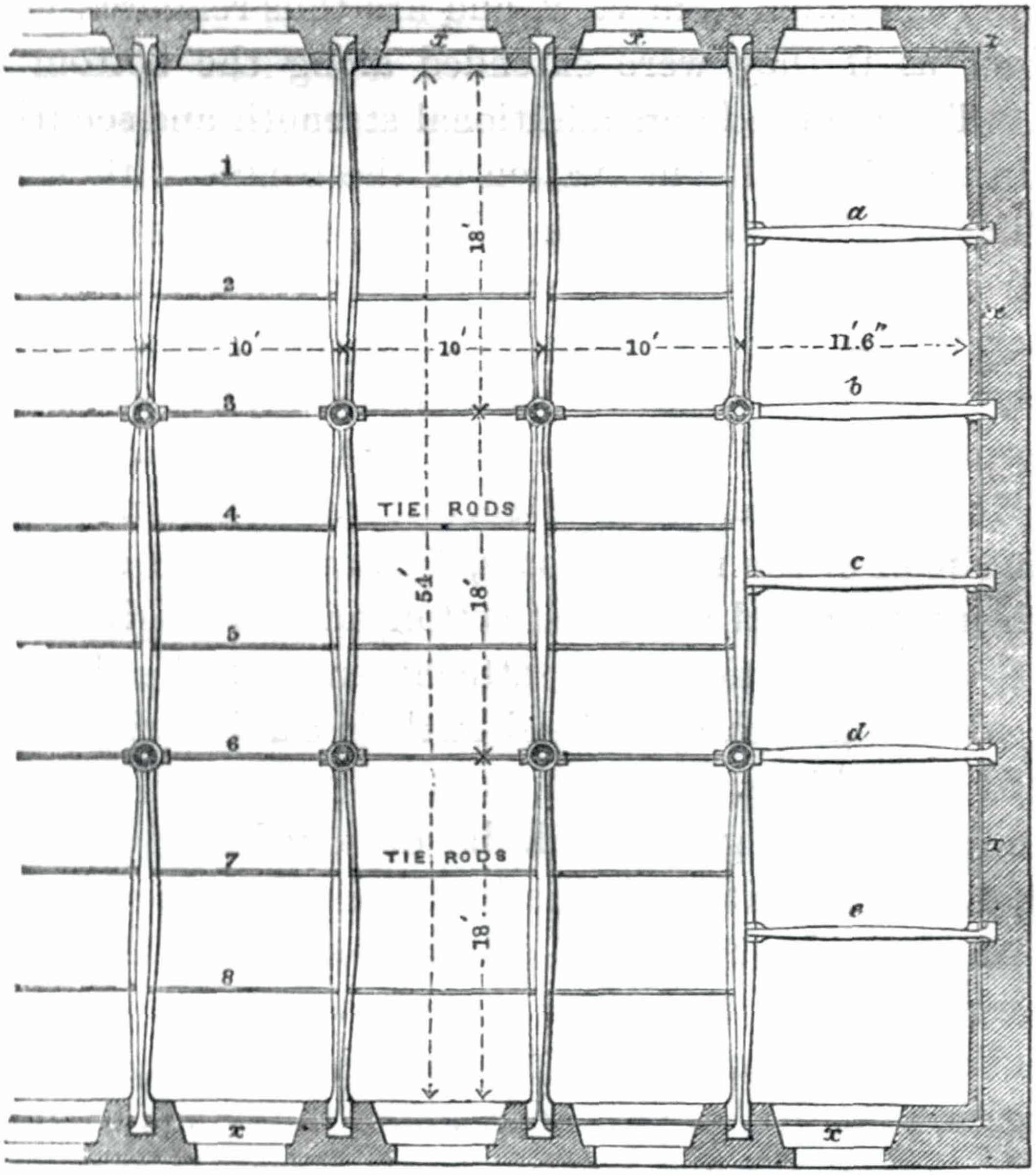


Illustration 229 Iron-framing to fireproof flooring (Source: Fairbairn, 1870)
Turned through ninety degrees, the end bay arches 'form a strong and powerful resisting abutment to the thrust of the transverse arches running from one end of the building to the other'.

(Illustration 228). Some of the floor dead weight may be carried by composite action if the beams are back-propped prior to placement of the concrete. To some extent the brickwork may be self-supporting between the columns by three-dimensional vaulting action.

In an arched floor the internal arch bays are mutually supporting. The thrust from the end bays is resisted either by a substantial solid masonry external wall (usually the gable wall), or by wrought iron ties to a cast iron 'thrust beam' built in to the wall. In some buildings, the arches to the end bays are turned through ninety degrees (Illustration 229).

A number of arched floors were patented. From the late 1840s, corrugated wrought iron arch formers were used in a number of building floors (Illustrations 230 and 231). Protected from the weather, the few surviving examples provide a rare opportunity to view riveted corrugated iron in close to its original condition. Gypsum combined with aggregate made 'Nottingham concrete'. This material, with excellent fire resistance, was used in Dennett's patent arch floor (Illustration 232). Dennett's business partner Mr F Ingle described the system as suitable for spans of 6' to 12', the arch thickness at the crown varying from 3" to

5", and the temporary arch formwork being removed after two to six days (Ingle, 1866). Although Dennett & Ingle were Nottingham-based building contractors, the 'Dennett floor' was quite widely used (Wermiel, 1993). Distributed load and impact tests were carried out on Dennett floors at Hackney Town Hall to satisfy the district surveyor. A 250 lb. block of stone dropped onto the 3$\frac{1}{2}$" thick crown of an arch from a height of 14' 'bruised, but did not break it' (Ingle, 1868). Moreland's of London patented a further variant, again using gypsum concrete and corrugated iron permanent formwork. Tests by the patentee to demonstrate the impact resistance of the Moreland floor involved the dropping of a 650 lb. weight from heights of 4' and 16' onto the crown and haunch respectively (Moreland, 1868).

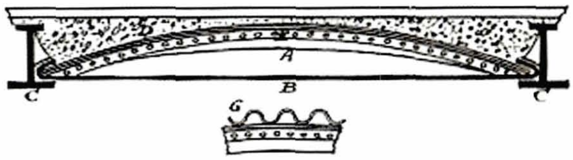


Illustration 230 Nasmyth's patent arch floor (1848)
Nasmyth of Pimlico, London, patented the use of plain or corrugated sheet iron as an arch former, topped with Portland cement concrete and finished with a tile or wood surface.
(Source: Potter, T. 'Concrete: its uses in building from foundations to finish', Batsford, London, 3rd edition, 1908, p177 Nasmyth's floor)

7.4.2 Plain slab floors and stairs

Stone landing slabs and stair treads are the norm in early nineteenth century multi-storey industrial buildings, whether of fireproof or traditional construction. The durability of stone stairs under the effects of pedestrian traffic has been proven over centuries in many pre-industrial buildings. In some eighteenth and nineteenth century houses, landings and small balconies of stone (and later in the period, concrete) cantilever from solid masonry walls. Later, plain concrete was used.

One writer reported the test of an unreinforced slab, with a 'four to one' concrete mix, 3" thick and cantilevering 3' 9" (Potter, 1908). The support comprised a chase or recess cut 3$\frac{1}{2}$" into 'an old wall'. Left for a year, the slab was then loaded with 107 lbs/ft^2

Illustration 231 The Great Eastern Hotel (Alexander's Mill), Duke Street, Glasgow (1848) Floor Details
Corrugated iron to the floor arches has the corrugations running in a perpendicular direction to Naysmith's patent illustration. The relatively small sheets, which must have been curved in the rolls in the direction of the corrugations prior to delivery to site, have carefully riveted side and end laps. The binder in the arch concrete appears to be gypsum rather than Portland cement. (Picture: Mark Watson, Historic Scotland)

(5.1 kN/m^2) 'without deflection or injury'. The calculated flexural tensile stress in the concrete at the root of the cantilever under the resultant total load is about 4.7 N/mm^2. Alarming, but perhaps no more so than the local stresses in the supporting masonry. Details of similar trials on plain concrete slab panels and cantilevers were given during the discussion following a paper to the Royal Institute of British Architects (Payne, 1876). For cantilever or 'hanging' stone stair treads, an 1876 text on building construction recommended that the ends 'should be let into the wall about 9 inches, and very solidly and firmly built in' (Rivington, 1876). Such steps are not true cantilevers as each derives some support from the rear edge of the step below.

Sandstone or slate was generally used in floors, the regular bedding planes allowing large slabs or flagstones to be split to an even thickness at the quarry. For British building sandstones, cube crushing strengths in the range 267 - 712 tons/ft^2 (29 N/mm^2 - 74 N/mm^2) have been obtained, and for slate 720 - 1974 tons/ft^2 (77 N/mm^2 - 212 N/mm^2) (Unwin, 1910). The strongest sandstone, 'York stone', was used extensively for the floors of the reconstructed spinning house, part of the Rope works, at Devonport Naval Dockyard in 1815 (Coad, 1983). For modern concrete, the tensile strength on which flexural strength depends is typically $^1/_{10}$ to $^1/_{12}$ of the cube crushing strength, but such a relationship can not be taken for granted for stone.

Coke breeze concrete came into use from the 1860s. Breeze, sometimes called coke ashes, or 'pumice', was the finer part of the coke from gas retorts. Towards the end of the nineteenth century, breeze was considered a very good aggregate for making fire-resistant concrete, but only if thoroughly burnt, and derived from a suitable quality of coal (Potter, 1907). Other materials used for aggregates included gravel from a variety of sources, stone chippings, boiler and furnace ashes, and when crushed to a suitable size, debris from quarries, brickyards, potteries and demolished buildings. A high sulphur content in furnace cinders and ashes would produce poor concrete and the satisfactory performance of other types of aggregate too was dependent on proper preparation.

Flat concrete slabs do not always contain iron or steel reinforcement. Many slabs were not reinforced, even in buildings of the structural steelwork era. An extension to a paper works in Edinburgh was built in 1897 with a plain concrete slab floor of 165mm thick, spanning 1.8m between Dorman Long steel beams.

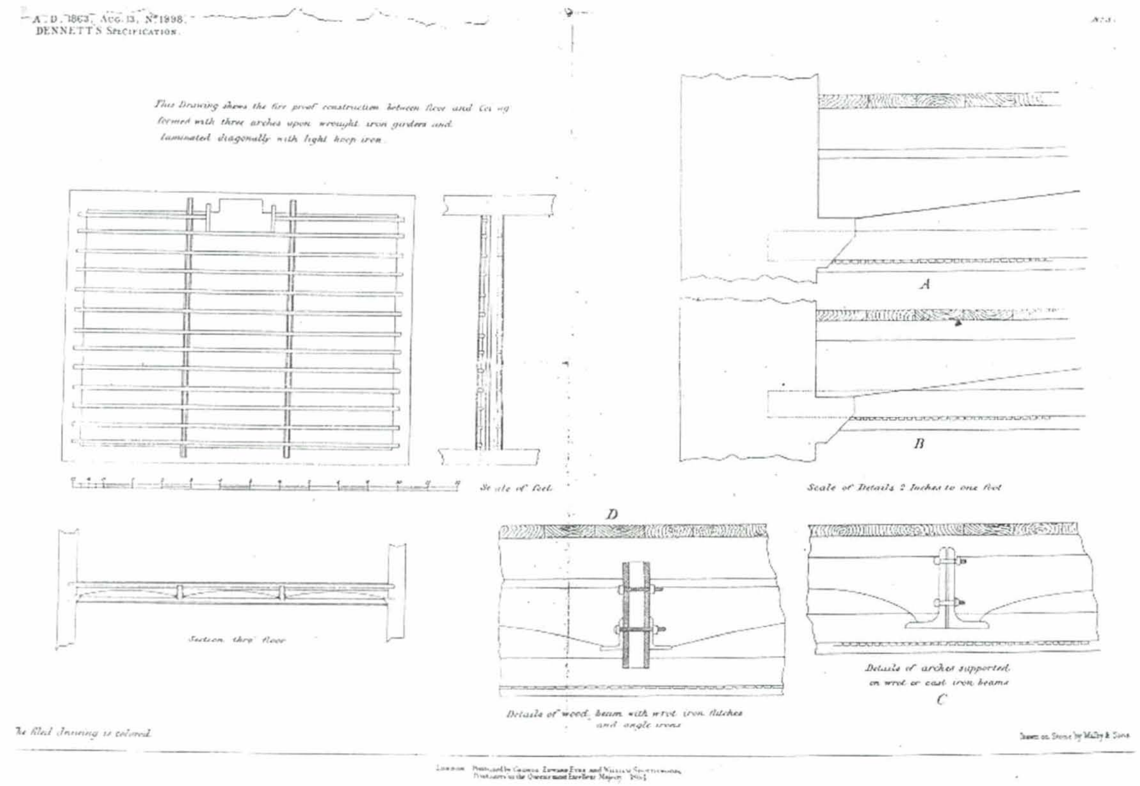


Illustration 232 Dennett's patent arch floor (1864) (Source: Patent number 1998, specification filed 19th January 1864, to Charles Colton Dennett, of Nottingham) This 'improved form of fireproof construction for buildings by the use of arches formed of concrete', was developed from a system introduced in 1857. The patent specification allowed for the support of unreinforced arches by wood beams, flitched beams, or iron girders on columns. No tying of the arches was specified. The concrete was to be made of 'sulphate or carbonate of lime (i.e. gypsum), together with broken calcined cinders, bricks, or other porous material'. Mix proportions were not given in the patent

The floor finish comprised boards on timber battens set slightly into the concrete. The aggregate, described as shale/slag colliery waste, contained a significant proportion of unburnt material. Assessed for conversion to offices in 1990, the fire resistance of the floor was a concern, but its strength was proved adequate by allowing for arching action within the slab. Calculated under working loads, the compressive stress in the concrete did not exceed 1.5N/mm^2.

Some interesting tests on 6" thick large rectangular concrete slabs were carried out by the Royal Engineers in 1874 (Seddon, 1880). The tests were carried out in such a way that little or no benefit was derived from arching action. A slab of 14' 6" by 13' 6" clear span was tested to destruction by piling with bricks, but first 'A party of 80 men marched on to it, marked time at quick and double, then jumped' (Illustration 233). A similar slab was tested by dropping a weight of 4 cwt from a height of 4' onto its centre. This 'punching shear' test broke a hole clean through the centre of the slab, 'but no radiating crack appeared, nor did the other portion of the slab appear injured'. Floors of this type were constructed in a series of Brigade Armoury Depots after the Cardwell reforms, the effect of which was to redistribute barracks around the country to promote local connections.

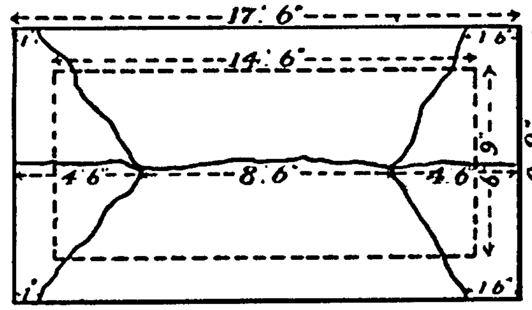


Illustration 233 Plain concrete slab tests by the Royal Engineers (1874)
Failure loads were determined for two different concrete mixes at 7, 14 and 21 days. The first mix was 1 part Portland cement, 4 parts broken brick ballast (gauged to an inch mesh) and the second mix 12 parts broken brick, 4 parts cement, and 3 parts sand. Where the crack patterns recorded at failure were close to the theoretical yield line pattern, a modern yield line analysis gives an average flexural tensile strength for the concrete of about 1.4 N/mm^2, under average uniformly distributed ultimate loads of 15.6 kN/m^2.

'Tile creasing' comprises layers of flat clay roofing tiles bedded in neat cement. After about 1835, extensively in London at least, tile creasing was used for flat roofs of modest span and for fireproof ceilings, sometimes arched (Hurst, 1996). Brunel's London office had a flat roof of 3 courses of plain tiles and cement, spanning 5'. In 1863, the roof to an 'ice house' in London's Caledonian Road collapsed during construction, with the supporting iron arches, under the weight of the workmen building it (Mitchell, 2001). The roof was square on plan, with sides of 13'. Four courses of tiles in cement made up a total thickness of 3". Layers of tiles were similarly used to form the shallow arched floors to Blakey's Mill.

7.4.3 Reinforced slab floors

There are patents that cover the reinforcement of early concrete slabs with joists of cast or wrought iron, with hoop or bar iron, or wire. In the last decade of the nineteenth century, steel in these and various other forms came into use (Bussell, 1996). From about 1830 to the end of the nineteenth century, 'hoop iron' was used at intervals in the bed joints of brickwork walls instead of bond timbers, which were susceptible to rot. Hoop iron sizes used were 1½" x 15 gauge (1.8mm) to ¾" x 20 gauge (1.0mm) (Hurst, 1996).

J C Loudon anticipated modern reinforced concrete, writing that 'floors and roofs might be made flat by means of a lattice work of iron tie rods, thickly embedded in cement or concrete and cased with flat tiles' (Potter, 1908). W B Wilkinson's patent of 1854 'Construction of fireproof buildings, etc.' mentioned the use of hoop iron as reinforcement for concrete floors. Wilkinson constructed a building in Newcastle, but his ideas seem not to have been adopted elsewhere (Illustrations 234 and 235).

Fireproof floors over rooms up to 20' by 25' in size were constructed in lunatic asylums in Wakefield and York in 1817 (Potter, 1908). Devised by Mr Pritchett, a Nottingham architect, flat arches or slabs of solid or hollow clay bricks were supported by inverted tee section cast iron joists spaced 4' 6" apart. With a reduced joist spacing of 18" or 2' and concrete infill between, Dr Henry Fox constructed a very effective composite floor for the private asylum that he built near Bristol in 1833. Patented in 1844, the floor, marketed by James Barrett, became known as the Fox & Barrett floor (Hurst, 1996). Although used mainly in London, the system received an unofficial royal seal of approval by its use in 'Her Majesty's New Highland Residence, Balmoral' (Barrett, 1854).

James Barrett was one of the first to use wrought iron joists in place of cast iron in the construction of floors. In the early 1850s, finding no rolls in existence for making equal I-section wrought iron joists, he had rolls prepared for sections of 4" to 8" deep. In the Fox & Barrett floor, coarse mortar was spread over and pressed down between closely spaced timber laths laid between the bottom flanges of the joists. This served as a key for ceiling plaster and as permanent formwork to

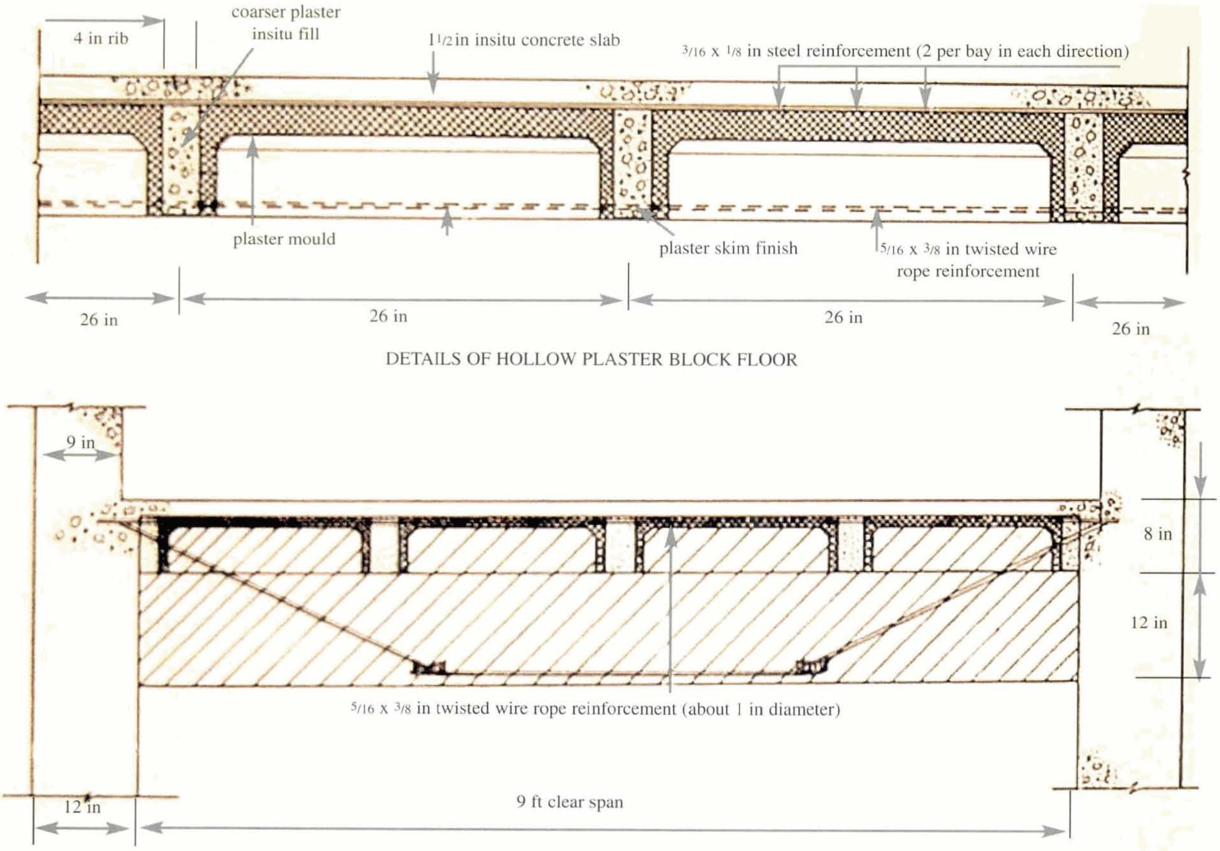


Illustration 234 Wilkinson's patent reinforced concrete floor, Newcastle (c.1865) (Picture: 'Structural Concrete')

the concrete. At the Royal Albert Hall in 1994, Fox & Barrett floors with wrought iron joists spanning 6m, performed satisfactorily under a proof-test load of 7.5 kN/m^2 (Stagg, 1994). Patents by Measures Bros. (1862) Phillips, Dawnay, and Gardner (Lawford, 1890) were later variants, all with small section joists or tee iron in place of the timber laths (Webster, 1891; Adams, c.1920).

Thomas Potter's practice for the construction of solid floors from 1869 was to use concrete deposited on a timber platform with temporary supports below. The concrete was finished flush with the top and bottom flanges of the supporting joists. Variants on this system used a thinner concrete slab, more as a fireproof ceiling, above which the top flange of the iron joists projected to support a floor of timber joists and boards (Illustration 236). Such systems, generically 'filler joist floors', had several advantages over brickwork arch and beam construction. The weight saving was very considerable, the construction depth less, and the ironwork more completely protected from the effects of fire.

In modern terms, with closely spaced supports, filler joist floor construction is an example of 'a load-sharing system'. Concentrated loads are very effectively shared between several joists. This was apparent in instrumented load tests on a c.1894 filler joist floor in a public library in Ashton-under-Lyne (Swailes, 1997). A particular kind of filler joist floor is found in some late nineteenth and early twentieth-century 'Oldham-type' mill buildings. Relatively small iron or steel joists

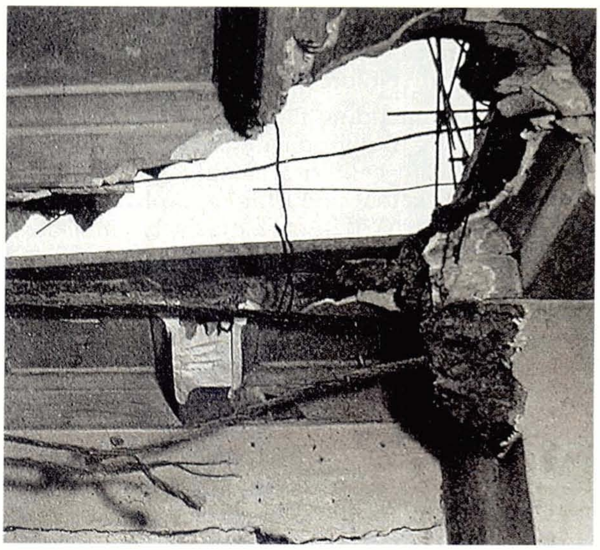


Illustration 235 Wilkinson's patent reinforced concrete floor, Newcastle (c.1865) (Picture: 'Structural Concrete')

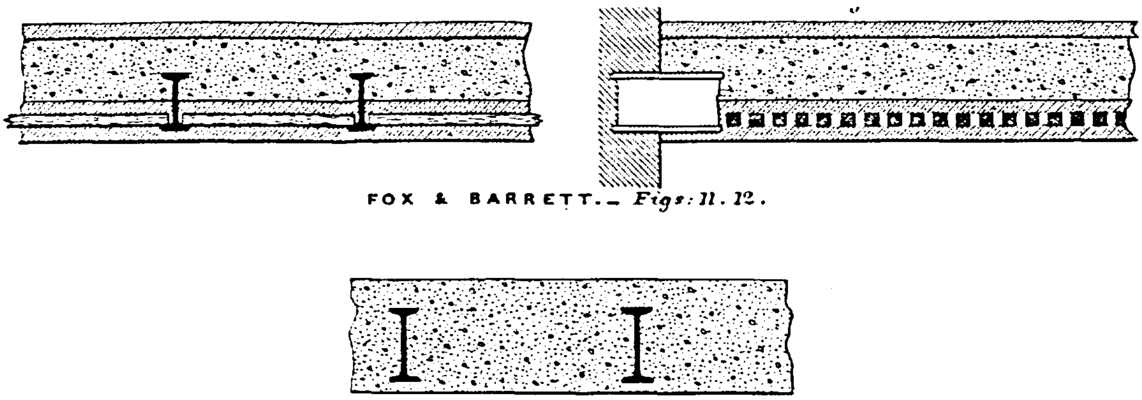


Illustration 236 Forms of filler joist floor

span around 10', as did the brickwork arches that they superseded. The joists are at close spacings and placed near the bottom of a slab of poor concrete of around twice their depth. Tests in the early 1920s showed that the safe working load for this type of floor, under certain circumstances, may be twice that obtained by considering the strength of the joists alone (Etchells, 1927). However, there have been cases where the infill between the joists has failed by punching shear under a concentrated load (Rhodes, 1987). In buildings other than mills, the iron or steel filler joists were generally of deeper section, only a little less than the depth of the concrete, and spaced further apart (Hurst, 1996).

7.4.4 Later patent floor systems

The great fire that ravaged Chicago in 1871 demonstrated to Americans that iron was not fireproof and the message was reinforced the following year by a disastrous fire in Boston, Massachusetts (Wermiel, 1993 and 2000). The devastating fire in Paris during the Siege and Commune of 1870-71 left a deep impression on the designers of commercial buildings in Britain. The requirements for fire protection to ironwork were now better appreciated, but more in city centres than in textile mill building, where construction practices were rather entrenched.

In most systems, pre-fabricated shaped blocks of hollow tile were supported between iron joists, to which they also provided protection. In the 1830s James Frost made square hollow tubes by machine for constructing floors and flat roofs, but probably for construction on a domestic scale without iron supports (Wermiel, 1993). Concrete was placed over and sometimes between the blocks, the soffits of which generally had dovetailed grooves to provide a key for the plastering mortar. Some of the better known floors, named after their patentees, include Bunnett (1858), Doulton-Peto, Fawcett (1888), Frazzi, Ferguson, Homan, Homan & Rodgers (1885, and several other dates), Hornblower (1871, 1873), Hyatt, King, Kleine, Lindsay, Northcroft (1876), Phillips, Statham, Swarbrick, Whichcord (c.1876) and Wilkinson (Illustration 237).

Clearly many 'beam and block' systems were patented, though many were probably not much used, or else their use was localised. To quote one authority, 'patents are ofttimes the result of theoretical vagaries which in actual practice are quite a failure' (Potter, 1908). More research is needed into the use of patent floor systems in Scotland. Hornblower's system was used in four or more buildings in Glasgow by John Honeyman, an architect active in the 1860s and 1870s (Cates, 1878). The structurally innovative and prolific Scottish architects Peddie & Kinnear used 'Fer Tubulair' in Dunblane Hydro, built from 1875-8, and in several other buildings. Exhibited at the 1857 Paris Exhibition, these tubular beams were the invention of F Zores, who had pioneered the rolling of I-section joists in France in 1848 (Chrimes, 1990).

7.5 Fire resistance and fire protection

7.5.1 Cast iron elements

The strength of cast iron reduces at high temperatures to a slightly lesser extent than steel. Working stresses are lower and sections are much heavier in cast iron than in steel, so cast iron elements perform well in comparison. There were many instances during the blitz of WWII of cast iron columns remaining standing after other parts of a building had been destroyed by fire (Evans, 1984). A famous case was that of New York's Wanamaker Department Store in 1956, the cast iron façade remaining intact although fire burned for almost a day and the interior of the building was destroyed. Such survivals do not change the fact that exposed cast iron has limitations in terms of fire

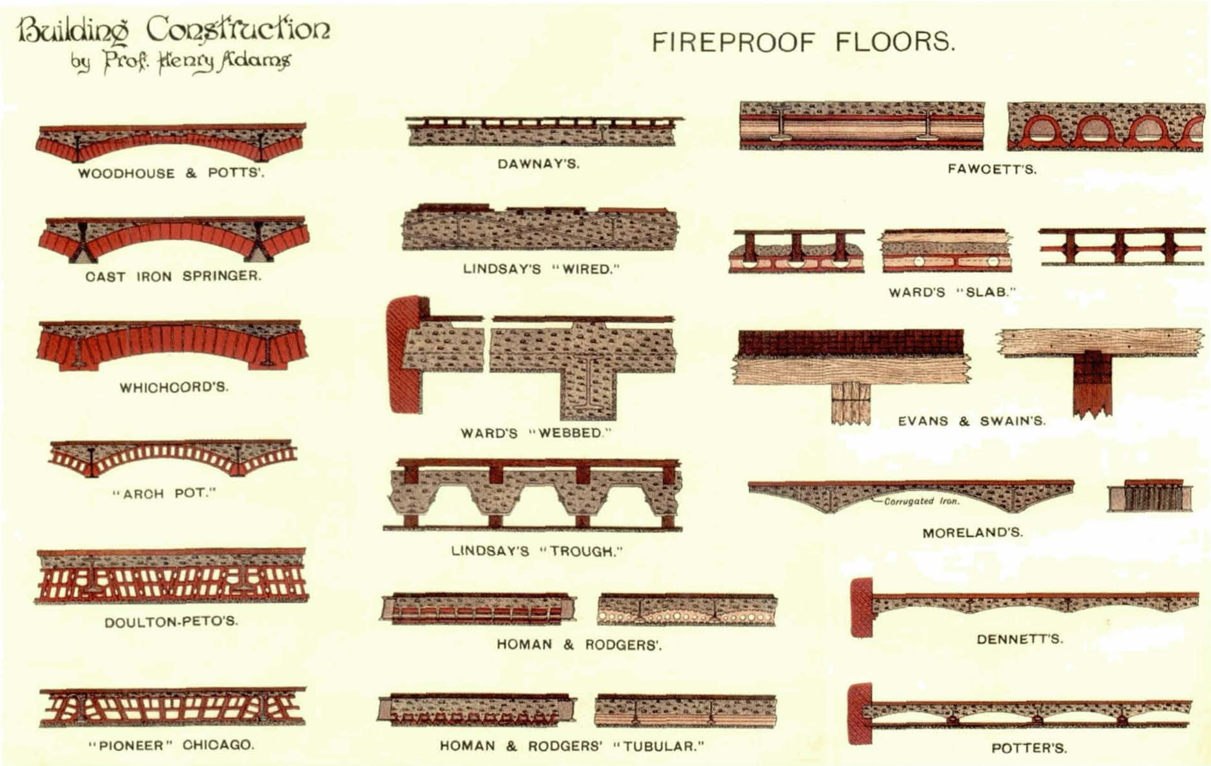


Illustration 237 Later patent floor systems (Source: Henry Adams; Building World Supplement, August 29th, 1903)

resistance, a fact appreciated from the 1870s onwards (Friedman, 1995). A particular concern has been resistance to cracking due to thermal shock caused by water from a firefighter's hose striking hot cast iron.

In tests for the Greater London Council in 1982-83, two unprotected Hodgkinson type cast iron beam sections of 4.07m simply supported span withstood the effects of a standard fire (BS476: 1987) for over an hour (Barnfield, 1984). Temperatures of around 860°C were achieved, under loads giving a bottom flange tensile stress of 23 N/mm^2 and causing a permanent deflection during the heating period of 150mm. On removal from the fire, the beams were cooled rapidly by a stream of water from a fireman's hose, with differential cooling producing substantial lateral bending. The top flange and upper part of the web of each beam cracked 10 minutes after application of the water and after the load had been removed. The beams did not fracture through their depth and were capable of being loaded again to the same level 24 hours later. The position of the thermal cracks suggests that tensile stresses were induced in the top flange as the larger bottom flange cooled more rapidly, probably from a higher temperature.

A subsequent study was carried out for the Greater London Council in 1986 on the performance of cast iron structural elements in real building fires (Porter, 1998). The general opinion of fire officers was found to be that cast iron performs well in fires and is less prone to collapse in the early stages of a fire than unprotected steelwork. The study concluded that cast iron beams were more prone to sudden failure and collapse than columns, especially if cooled rapidly when hot (Illustration 238). However, it was concluded that firemen by their experience and training were aware of this hazard and were careful when fighting fires in cast iron framed buildings.

Using a 'fire engineering' approach, the exposure of more lightly loaded elements without fire protection may be justifiable. Tests in Germany examined the fire resistance of columns for different levels of concentric loading (Twilt, 2000). An unprotected hollow cast iron column achieved 30 minutes fire resistance at full load, and 50 minutes at half that load. Grouting of the core with concrete gave only a small increase in fire resistance, while an intumescent coating proved to be far more effective.

The only type of fire protection that allows ironwork that is exposed to remain so, is the application of an intumescent paint coating to the prepared surface of the metal. Intumescent paint 'foams' on heating to form an insulating layer. Relatively thin film coatings can provide up to 1½ hours fire resistance without at the same time blunting the finer features of a casting (English Heritage, 1997). A cruciform section cast iron column from a London warehouse achieved a fire resistance of 1 hour in a furnace test and also withstood quenching tests (Baxter, 1984). The columns were provided with a further 2 hours fire resistance in the converted warehouse by applying intumescent mastic.

Where cast iron elements survive a building fire, questions will be asked about their future safety (Illustrations 239 to 241). Creep will first occur at temperatures of around 400°C and, after a fire, cast iron columns may be left with a permanent 'bow'. A hollow column of 127mm outside diameter, removed after a fire at Stanley Mills, was found to be bowed or 'out of straight' by 40mm in a length of 3m (Illustration 242). Testing confirmed that the cast iron had not been heated sufficiently in the fire to cause any measurable reduction in the strength of the material (see also Section 5.3.4). In large hollow circular columns, local buckling or bulging of the relatively thin column wall may take place (Illustration 243). Clearly in some cases distortion will be so severe that retention or reuse of a cast iron column is not an option.

Cracking sometimes occurs as a result of restrained thermal movement. Thermal cracks in columns may be repairable by the methods outlined in Section 8, but cracks in beams, or the possibility of cracks, are more problematic. Surface hairline cracks can form on cooling, as the surface layer cools and contracts more rapidly than the material beneath. It has been suggested that such cracks can open up when a cast iron beam is reloaded, with catastrophic consequences, and that any beams heated to 350°C or above in a fire should be regarded as suspect (Kirby, 1986). It is possible to prove an absence of 'surface' shrinkage cracks after a fire by using non-destructive testing techniques.

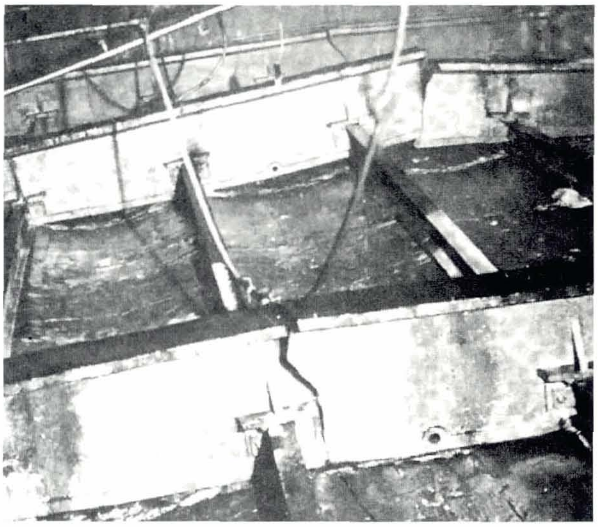


Illustration 238 Brittle fracture of cast iron beams as a result of fire and fire fighting (Kirby, 1986) (Picture: Mr. C. Ashton, reproduced by permission of Corus (UK) Ltd)

7.5.2 Wrought iron elements

The performance on structural wrought iron in fire is very similar to modern mild steel, for which a considerable volume of technical guidance is available. Wrought iron is not permanently weakened by exposure to high temperatures, and it may be possible to straighten elements that become distorted as a result of fire (See Section 5.2).

7.5.3 Floor construction materials

(a) Timber joists and boards

Large timbers will withstand the effects of fire for some time but joists and boards are generally protected. In 1773, David Hartley, the MP for Hull, was granted a patent for a system in which wrought iron sheets, typically 0.3mm thick × 450mm wide, were fixed above and sometimes below timber floor joists, which generally had dry sand or rubbish placed

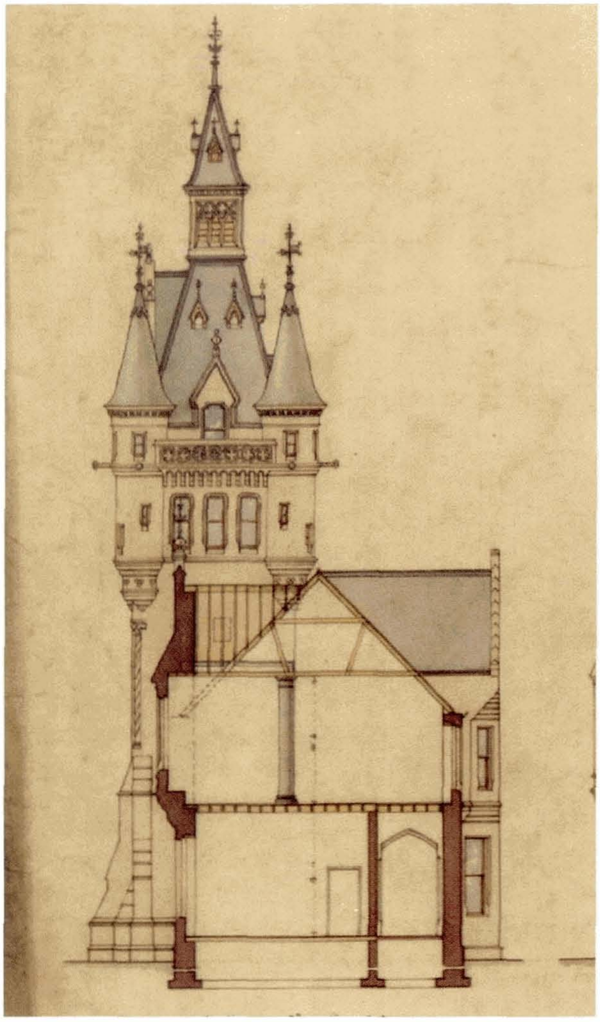


Illustration 239 Morgan Academy, Dundee (1868) Peddie & Kinnear Drawing extract (Reproduced courtesy of RCAHMS (Dick Peddie and McKay Collection))

Illustration 240 Morgan Academy, Dundee (1868) Fire (Picture: DC Thomson and Co)

between them (Kelsall, 1991). 'Hartley's fire plates' were probably little used in the way intended, but wrought iron sheets are quite often found as soffit protection to timber floors and ceilings in textile mills

Gypsum plaster is a traditional method for providing a fire resistant decorative finish. Filling the spaces below the floorboards and between the joists with lath and plaster was proposed by Lord Mahon in the eighteenth century, as a kind of 'pugging', later used more as a sound proofing measure. In Nottinghamshire and Derbyshire fire-resistant floors that pre-dated the industrial revolution used coarse plaster made with locally quarried gypsum as a binding material for timber joists, reeds or laths. H J Stevens of Derby gave details during discussions at the Royal Institute of British Architects (Barrett, 1854).

Illustration 241 Morgan Academy, Dundee (1868) Tower after fire (Picture: Mark Watson, Historic Scotland)

Illustration 242 Stanley Mills. Cast iron column bent in fire (Picture: T. Swailes)

Illustration 243 Local bulging at the tops of cast iron columns as the results of high temperatures reached during a particularly severe fire (Kirby, 1986)
(Picture: Mr. C. Ashton, reproduced by permission of Corus (UK) Ltd)

(b) Brickwork and fired clay blocks

As bricks are exposed to very high temperatures in a kiln during manufacture, they generally have good fire resistance. In brickwork arch floors the encased parts of the supporting beams are quite well protected. For a recent refurbishment project, a fire-engineering approach enabled cast-iron beams with unprotected soffits to be justified for a fire-resistance of 1 hour (Bussell, 1998). It was found that in the event of a fire, the solid floor structure would act as a 'heat sink', limiting the temperature of the cast iron to an acceptable level.

Whichcord's system was subjected to a fire test at engineering firm Easton & Anderson's Erith Iron Works, in Kent (The Engineer, 1874). A rolled wrought iron joist, 17' long × 10" deep × 5" wide, weighing 7 cwt, was laid across a furnace and encased with Whichcord's fired clay blocks. The joist, supporting an arched floor of blocks and loaded to 1/4 of its breaking load with pig iron, withstood an intense fire for 2 1/2 hours with only a gradual increase in deflection. After the test the joist was still useable.

(c) Stone

Tests in the nineteenth century showed that although sandstone resisted heat better than other types of stone, its fire-resistance was greatly inferior to that of brick (Webster, 1891). According to an 1876 text on building construction, 'Stone is a very bad material for fireproof structures; when subjected to great heat it suddenly cracks, and gives way without warning'. Stone stairs and landings were used principally for their solidity, wear resistance and incombustibility as 'the destruction of stone steps by fire, though not so rapid, is quite as effectual as if they were made of wood' (Rivington, 1876).

One early floor combined wrought iron and York stone (sandstone). The system was described when James Barrett presented a paper on floor construction systems in the 1850s (Barrett, 1854). Many years previously Mr Tite, an architect, had used inverted tee sections of riveted wrought iron spanning 15' and spaced 4' apart in the floor of a large public school. York stone slabs, 4" to 6" thick, were laid on the flanges of the tees. Roman cement was used to fill the gaps and form the ceiling. This was along the lines of the patent (c.1826) of a Mr Farrell, a smith on Robert Smirke's Customs House, who distrusted cast iron girders. The arrangement was severely criticised by several architects dubious about the fire-resistance of the stone. One had used this form of construction in his own property, but had not done so again, 'observing that York stone paving was exceedingly destructible by fire, and that practically it did not furnish a fire-proof floor'.

(d) Concrete

Concrete is a loose term embracing a great variety of materials. Early concrete in particular may contain combustible materials and fire resisting properties on a par with modern Portland cement concrete should not be automatically assumed (see also Section 7.4.2).

A fire in a six-storey London building in 1871 provided an early demonstration of the fire resistance of good concrete. Damage to the building was described thus; 'The iron doors, columns, girders, floors and roof, and all the ordinary stonework were destroyed, and even the granite paving of the courtyard was damaged. York (sandstone) landings 3 feet by 8 feet and 6 inches thick, forming the cills under the iron doors were entirely destroyed, while the concrete lintels above, which had been exposed to a much fiercer heat, were quite unhurt' (Cates, 1878). In this case the concrete was to Mr Allen's patent specification of 1862, with one part of Portland or other cement and six to eight parts cinders, slag-coke, or clinker (Webster, 1891). Subsequent buildings for the affected owners were built with concrete floors and with concrete encasement to all iron columns and girders.

7.5.4 Whole building considerations

At a temperature of 600°C, cast iron loses about half its strength and the length of a 4m long beam of cast iron (or wrought iron or steel) would increase by about 25mm. Even though an individual beam may possess good fire resistance in itself, it is necessary to consider how the various parts of a building structure interact during a fire. There are many unknowns. For example, what forces are exerted on the supports of a beam, as they tend to restrain its thermal expansion? One conclusion of studies for the Greater London Council in the 1980s was that there was no realistic alternative to fire protection of cast iron elements in buildings in which there is a significant fire load, such as shops and offices, hotel bedrooms and domestic dwellings.

Of course, every effort should be made to prevent fires from occurring in the first place. Lessons learned from a serious fire at Windsor Castle in 1992 were incorporated in an updated Fire Protection Association Guide on the protection of historic buildings (Kidd, 1995). Although fire safety legislation in the UK is concerned principally with the protection of life, the loss of historic buildings and their contents by fire is particularly significant, as once lost, they can not be replaced. Historic Scotland TAN 11 gives guidance on identifying and eliminating fire risks in historic buildings and reviews available fire detection and protection solutions (Allwinkle, 1997). Advice is given on choosing fire prevention measures that involve an acceptable level of intervention in the historic fabric of a building. TAN 22 is concerned specifically with fire

Illustration 244 Fire fighting at a distance (Picture: DC Thomson and Co)

risk management in 'heritage buildings', a term that includes historic buildings as well as buildings that house historic collections, such as museums, galleries, libraries and archives (Kidd, 2001). Risk assessment approaches are explained that aim to reduce the risk of fire, and also aim to minimise fire damage to historic building fabric or contents.

The installation of sprinkler systems in historic buildings is considered in Historic Scotland TAN 14. In empty multi-storey industrial buildings, the remains of fire detection and sprinkler systems are quite likely to be present, but no longer providing protection to the building. Empty non-fireproof factories and warehouses are at great risk. It is vitally important that building security be maintained to prevent the unauthorised entry of anyone who might deliberately or accidentally start a fire, as any fire is likely to develop and spread undetected. Once a fire takes hold in a large building, it is very difficult for the Fire Brigade to get close enough to stop its destructive progress (Illustration 244). Structural ironwork components are quite likely to survive a fire unscathed. Unfortunately, the skills of the founder who made them and the builder who used them are not reflected in their scrap value (Illustrations 245 & 246).

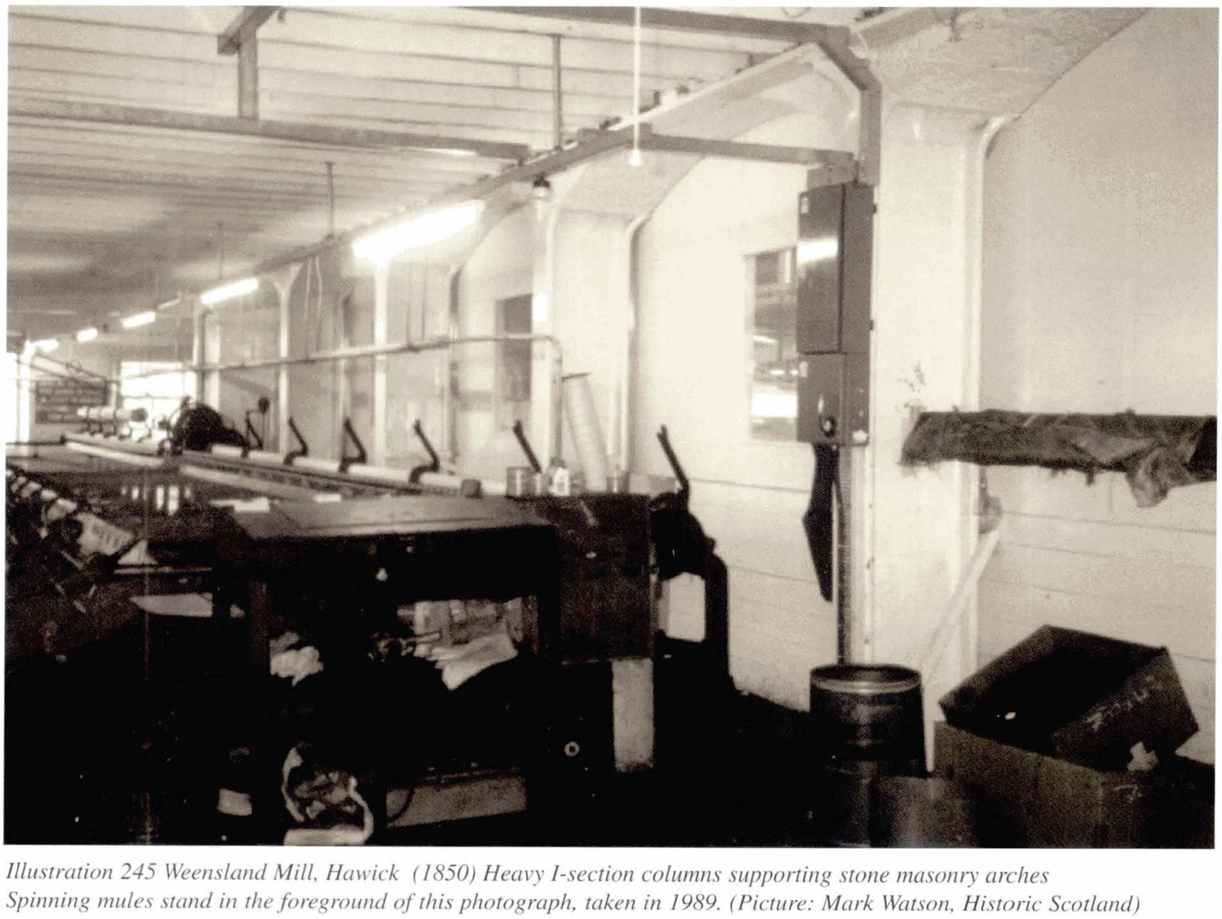


Illustration 245 Weensland Mill, Hawick (1850) Heavy I-section columns supporting stone masonry arches Spinning mules stand in the foreground of this photograph, taken in 1989. (Picture: Mark Watson, Historic Scotland)

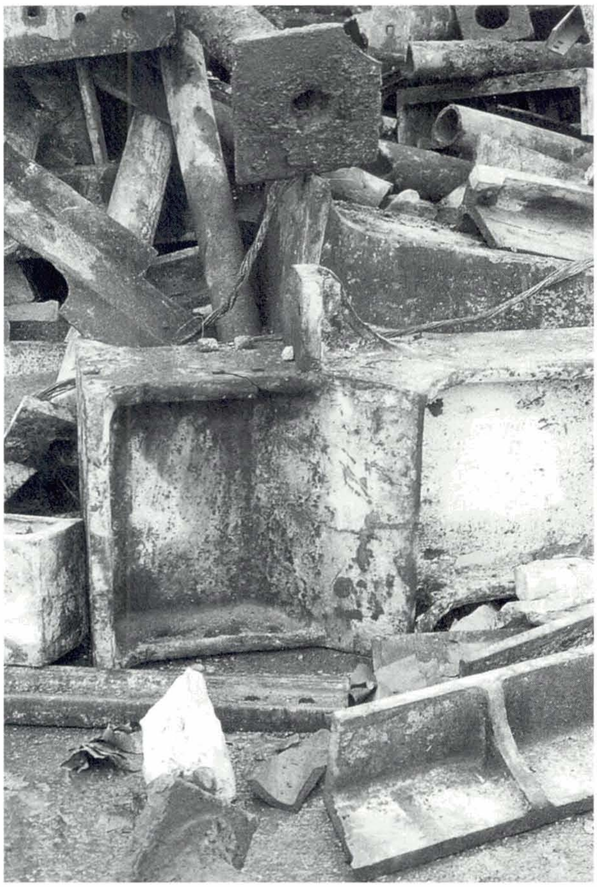


Illustration 246 Weensland Mill, Hawick (1850) Heavy I-section columns on the scrap heap, after destruction of the building by fire (Picture: T. Swailes)

7.5.5 An historical perspective on fireproof buildings and fire

There were alternatives to iron framing in the nineteenth century and its opponents increased in number after the collapse of Radcliffe's cotton mill near Oldham in 1844 (see Illustration 46). James Braidwood's view of iron framed buildings was that 'unless scientifically constructed, they are very unlikely to be safe, independent of the risk of fire' (Braidwood, 1849). In the event of fire, exposed ironwork was certainly not fireproof. American visitors in the latter part of the nineteenth century were surprised at the lack of fire protection to structural iron in British factory buildings (Wermiel, 1993).

In the United States, 'slow-burning' construction was used for most factories, rather than the various forms of fully iron-framed 'fireproof' construction used throughout Britain. Heavy timbers burn slowly, charcoal to their exposed faces insulating sound timber beneath. In 1871 and 1873, Thaddeus Hyatt obtained British patents for a 'slow-burning' floor system. In 1876 Evans & Swain patented a further variant (Cates, 1878). Joists 2" or 3" thick were spiked together side by side and their soffits rebated to provide a key for a thick plaster render. Alternatively, the key for the plaster might be provided by flat headed nails driven into the undersides of the joists. Slow-burning construction was used, in combination with timber storey posts, in the construction of several warehouses in London's East India Docks. The original proposal had been for concrete floor arches on wrought iron girders, supported on cast iron columns with a 4" of terracotta as fire-protection.

James Braidwood reported that 'after a fire at a sugar-house at Leith, which was built on the usual fire-proof principle, with iron columns and girders and brick arches, nothing remained but a heap of ruins' (Braidwood, 1849). Braidwood was a strong advocate of the modern principle of 'compartmentation' to limit the size and spread of any fire to manageable proportions. Taking the firefighters' point of view, he believed that warehouses should be 'of a moderate size, with access on two sides at least, completely separated from each other by part walls, and protected by iron doors and window shutters'.

Braidwood, the son of an Edinburgh builder, was Superintendent of the Edinburgh Fire Engines during the 'Great Fire of Edinburgh' in November 1824. After reforming the Edinburgh fire service, placing emphasis on effective alarms and a rapid response, Braidwood moved to London (Henham, 2000). Braidwood's report on the fire that destroyed the Houses of Parliament was one of the factors that led to their reconstruction on fireproof principles, with cast iron framing on a hitherto unprecedented scale. In 1854, Braidwood wrote to the Commissioner of Public Works on proposals for a large jute warehouse in the London docklands; 'The whole building, if once fairly on fire in one floor, will become such a mass of fire, that there is now no power in London capable of extinguishing it, or even of restraining its ravages on every side, and on three sides it will be surrounded by property of immense value'. Braidwood's words were tragically prophetic, as the building was destroyed by fire in 1861, it's fall causing an explosion in an adjacent building containing highly flammable tallow, tar and resin, which in turn set fire to other warehouses and buildings. Braidwood was one of six firefighters who died trying to subdue the blaze.

8 CONSERVATION AND REPAIR

8.1 General principles

The study of the cultural significance of a building and its surroundings is broad in nature and sometimes involves disciplines not normally associated with the construction industry. Generally, a construction professional with expertise in building conservation will use facts and opinions from a variety of sources in drawing up an overall conservation or maintenance plan. Sometimes the input of a structural engineer will be essential. For example, restriction of the uses of the upper floors of a building is a conservation measure that might prevent damage to ceiling finishes due to excessive deflections.

Once a conservation project is under way, a proper level of professional direction and supervision must be maintained through to completion. A log should be kept of the work carried out. Any new evidence or unexpected forms of construction found during the course of the work should be recorded, particularly if they make necessary an approved departure from the original plan. Generally, the disturbance of fabric to assist the study of a building should only be undertaken to obtain data essential for decisions on its conservation. In the case of an iron-framed building with a filler joist, or concrete and ash, or flagstone floor, wholesale replacement of the original material would lose archaeological evidence. There may be a case for disturbance of fabric to secure evidence about to be lost, or made inaccessible, through necessary conservation or other unavoidable action. Destructive investigation that adds substantially to a scientific body of knowledge may be permitted, provided that it is consistent with the overall conservation policy for the building. A record, possibly involving materials sampling and testing, should be made in these circumstances. When hidden structural iron framing details are exposed, it may be valuable and aesthetically pleasing to leave some examples uncovered for future study, fire-resistance requirements permitting. The ramp that wraps around the columns to form the public entrance to New Lanark Mill 3 is an example of what can be done. (Illustration 36).

A fundamental principle of conservation is respect for the existing fabric, which determines that conservation actions should involve the least possible physical intervention. In particular, they should not distort the evidence provided by the fabric. When this principle is applied to the conservation of ironwork, it favours the in-situ repair of ironwork rather than its replacement with, for example, new castings, or with re-cycled wrought iron. Sometimes replacement of iron elements will be necessary to ensure structural integrity. For decorative ironwork, retention and repair of the existing fabric rarely compromises the aesthetic integrity of a building.

Illustration 247 Spalling and (structural?) repair of stone balcony slab, caused by expansion (thermal or corrosion related?) of inset cast iron railings (Picture: T. Swailes)

Techniques employed should usually be traditional, although in some circumstances they may be modern ones for which a firm scientific basis exists and which are supported by a body of experience. For example, resin-bonded carbon fibre reinforcement, as used on concrete motorway bridges, is a new technique very recently tried on iron bridges, is reversible and may revolutionise the performance of historic iron structures. While it is important to stay abreast of the development of novel repair techniques, historic buildings are not suitable subjects for experimentation. That is not to say that building conservation is backward looking, as much scientific research is being carried out into the properties of materials, processes of degradation and methods of preservation. Great advances are now being made in the conservation of modern materials, including metals.

Iron is invariably found alongside other materials, including timber, masonry and glass, so its

Illustration 248 Damage to iron railings in Glasgow
Failure to weed out vegetation from beneath the coping has resulted in avoidable damage.
(Picture: Jacobs Babtie)

Illustration 249 Beam web loss due to corrosion
A patent block floor over a neglected basement, supported (just) by a severely corroded wrought iron or steel beam.
(Picture: Joe Marsh)

conservation should not be considered in isolation. The neglect or inappropriate treatment of one part of a building often leads to the deterioration of other parts. Putting off apparently trivial regular maintenance tasks can lead to unnecessary repair works that have a cost out of proportion to their cause (Illustration 248). Once damage has been caused to masonry it may be extremely difficult to repair in a satisfactory manner (Illustration 247). Basements and covered light wells should not be neglected, as they can provide environments where corrosion can progress unseen, to a point where structural safety is compromised (Illustration 249).

8.2 Listed Building Consent

Where a building is listed, at whatever category (A, B or C(S)), demolition or alterations in such a way as to affect its character will require Listed Building Consent. The relevant local authority planning department will be able to advise whether the works proposed require Listed Building Consent. Except in cases relating to category C(S) buildings, once a council has determined an application that decision is notified to Historic Scotland. It is often advisable to involve Historic Scotland's Inspectorate early in discussions relating to significant changes. Whether or not the particular element affected is mentioned in the non-statutory list description has no bearing on whether listed building consent is required. Frequently, interiors will not have been inspected, and some list descriptions are more perfunctory than others.

Works to iron structures that fall into this category can include façade retention, dismantling, relocation, over-cladding (e.g. false ceilings or encasement as fire protection), and removal of pillars from shopfronts or within buildings. In cases of bridges, strengthening or widening is often desired, or the replacement or protection of parapets. Works purely of repair (in a like material) that do not affect the character of a listed building do not require Listed Building Consent. As a rule of thumb, additional fabric, such as carbon-fibre resin bonded to iron, or a lightweight reinforced concrete mesh overlying a floor is likely to be unobtrusive and reversible and may not on its own require Listed Building Consent. On the other hand replacement of elements, e.g. steel or GRC in place of iron, is a matter for listed building consent and will need careful consideration and justification.

Some case histories regarding iron structures can offer guidance, although each application will be treated on its own merits as well as by reference to the Memorandum of Guidance on listed Buildings and Conservation Areas (1998). A proposal to replace the arched cast iron Carron Bridge in steel, and refix the external ribs to the new structure, was called in the Secretary of State for Scotland and then withdrawn during a Public Local Inquiry. On the other hand this action has been accepted as part of widening programmes for smaller and lower-lying bridges, such as Bridge of Newe, Aberdeenshire. A proposal to demolish and rebuild behind the four façades of West Bridge Mill, Kirkcaldy, and install new structure, basically because engineers were unfamiliar with and lacked confidence in the iron frame, was amended to one retaining the structure (at much lesser cost) in order to allow the granting of listed building consent for the conversion to West Bridge Foyer. A similar situation was narrowly averted, in part thanks to the second opinion of consulting engineers, in the case of Gardner's warehouse, Jamaica Street, Glasgow. On the other hand listed building consents for façade retention have occasionally been granted where it is concluded that the interest of the structure per se does not over-ride the imperative to add value, increase floor-loadings, and sometimes additional storeys. Early consultation with the planning authority and with the Historic Scotland's Inspectorate is therefore recommended.

8.3 Conservation Areas

Applications to demolish any building within a conservation area require Conservation Area Consent. This will not usually be determined without consideration of the impact of the existing building and of the proposed development on the character of the conservation area. The relevant Conservation Area Character Appraisal should be consulted, if available. It may for example give particular emphasis to the contribution made to that character by iron in railings, brattishing or shopfronts, which would then give greater importance to the retention, or reinstatement if missing, of these features.

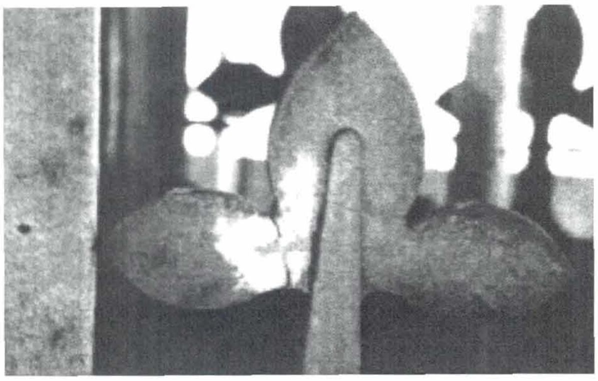


Illustration 250 Cold stitch repairs
A wrought iron stitch repair of a damaged decorative casting (Picture: Dorothea Restorations Ltd)

8.4 Scheduled Monument Consent

Any work, both of alteration and repair, to a Scheduled Ancient Monument requires Scheduled Monument Consent from Scottish Ministers. Advice on this is available from Historic Scotland's Inspectorate.

8.5 Mechanical repair and strengthening

Cracked castings are often repaired mechanically to avoid the thermal stresses and distortions associated with welding. However, the cause of cracking needs to be established before an appropriate form of repair can be chosen. Cracking releases stresses and a repaired casting may crack again, either at the repair or somewhere else, if the stresses that caused the cracking are not eliminated or reduced.

The blacksmith's repair to cracked cast iron is a wrought iron stitch (Illustration 250) (Wallis, 1999). In the modern version of this, for castings thicker than 6mm, shaped keys of ductile alloy are used. These are fitted across the fracture into holes pre-formed by a combination of drilling and pneumatic chiselling. Across the fracture and along its length, interlocking studs are screwed into the drilled and tapped holes. Such repair techniques have been established for over 50 years and are the province of the specialist contractor. However, guarantees of structural performance should be treated with suspicion, particularly if offered without proof-testing. On completion of a stitch repair, the surface may be finished flush to render the repair almost invisible (Illustrations 251 & 252). The restoration of the 1816 Ha'penny Bridge over the Liffey in Dublin is an example of a recent project where crack stitching of cast iron was among the repair techniques used (Cox, 2002; de Courcy, 1991).

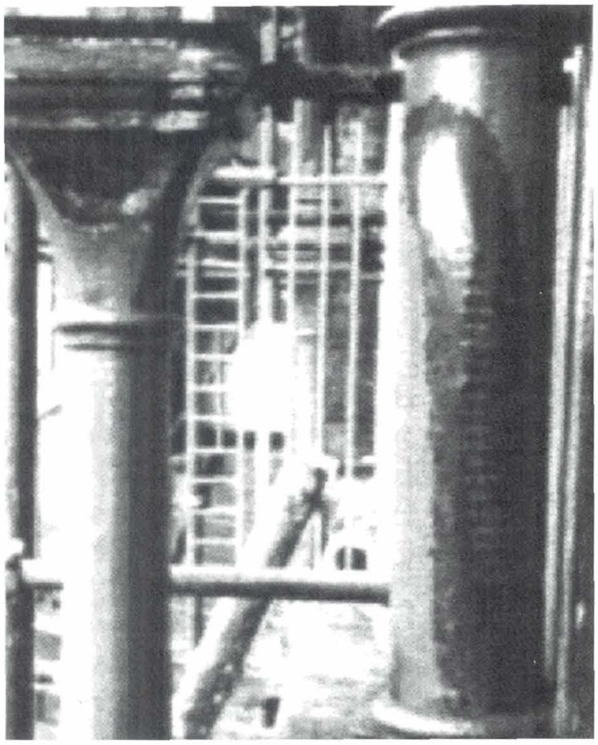


Illustration 251 Cold stitch repairs
A cold stitched repair to a cracked cast iron column (Picture: Dorothea Restorations Ltd)

Mechanical cold repairs to castings involve the limited removal of some original material. Where additional strength is required, one solution is to bolt on additional material to make a sufficiently robust repair (Illustration 253). Decorative cast iron panels, probably too thin to weld, have been successfully repaired by bolting 2mm thick galvanised steel backing plates to

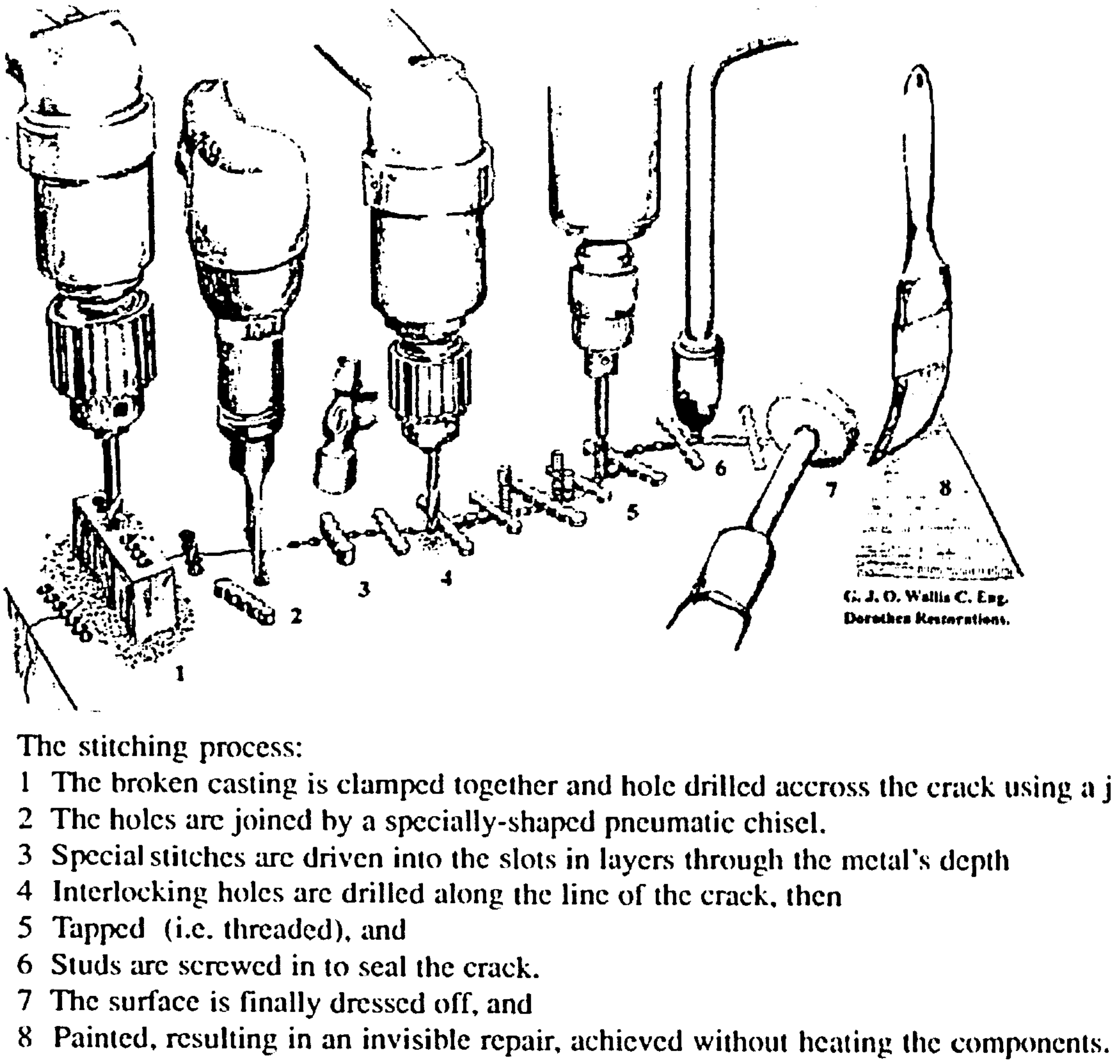


Illustration 252 Cold stitch repairs The stitching process (Picture: Dorothea Restorations Ltd)

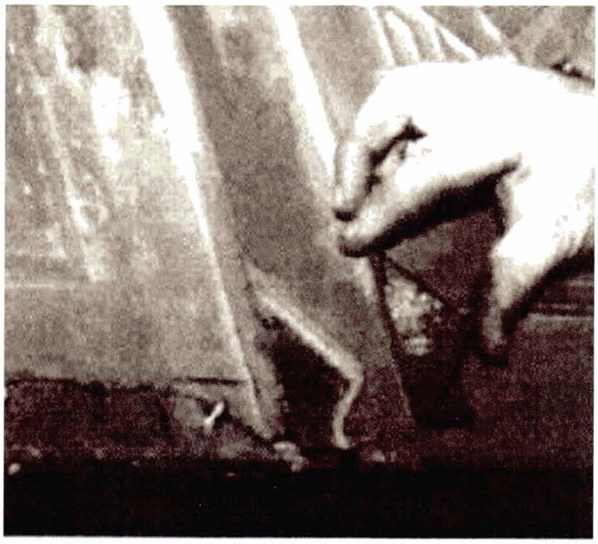
their plain inside faces. The reinforcing plates were bedded in resin and sealed round. Aesthetics were not generally considered in past repairs to industrial structures, but such past repairs should be left as found where possible (Illustrations 254 and 255).

8.6 Surface bonded reinforcement

According to a recent Institution of Structural Engineers guide, the largest use of adhesives in civil engineering, over 75%, is in repairs (IStructE, 1999). Several weak cast iron bridges have been strengthened with surface bonded reinforcement. Bures Bridge in Suffolk was strengthened by gluing steel plates to the arched soffits of cast iron deck beams (Robbins, 1991). Bonded steel sections were used to stiffen slender cast iron struts and bracing diaphragms in Thomas Telford's 1826 Mythe Bridge over the River Severn (Bolton, 1992).

More recently, carbon fibre reinforced polymer composites (CFRP) have been used by London Underground Ltd for short-term temporary repairs to cast iron bridge beams and to add additional stiffness to very large-section cast iron retaining wall props (Moy, 2001). To relieve a proportion of the dead load stresses in weak cast iron beams, trials have also been made on the application of pre-stressed externally bonded reinforcement. The 1874 Hythe Bridge, Oxford, was strengthened with 4mm thick prestressed carbon fibre strip applied to the soffits of cast iron girders. Thomas Wilson's 1810 Tickford Bridge in Northamptonshire, made by Walker & Co. of Rotherham, was strengthened using carbon fibre reinforced bandaging (Tilly, 2002).

The use of adhesives and high strength modern materials is a promising and potentially reversible strengthening technique, but long-term performance



An unusual conservation project: a gentleman's toilet in central London, made of cast iron panels only 6mm thick. Conservation work included a broken panel which was repaired by bolting to backing plate of galvanised steel 2mm thick bedded on resin and sealed round. If such a thin plate of cast iron had been welded, it would have cracked repeatedly: welding is not recommended for thin sections.

Illustration 253 Cold repair and reinforcement by plating
A broken decorative cast iron panel reinforced with a stainless steel backing plate.
(Picture: Dorothea Restorations Ltd)

Illustration 254 Cold repair and reinforcement by plating
Old repair to damaged cast iron I-section stanchion
(Picture: Michael Bussell)

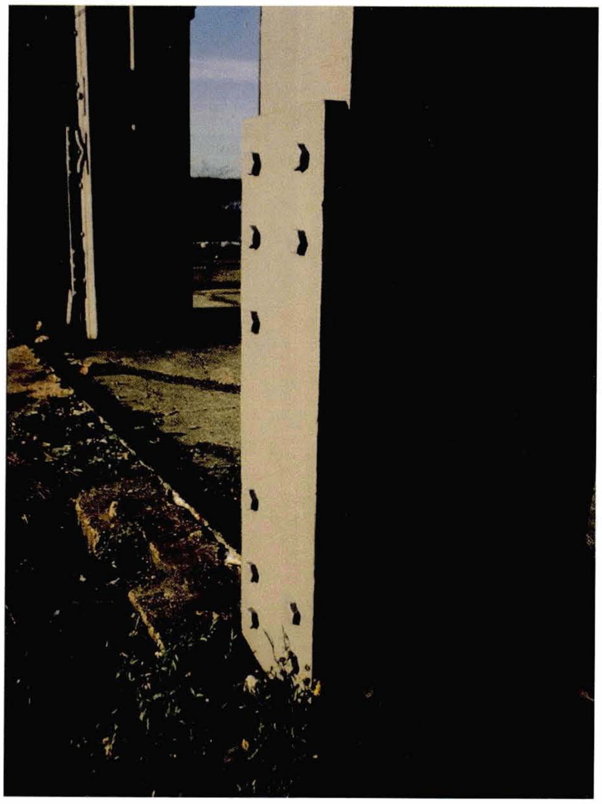


Illustration 255 Cold repair and reinforcement by plating
Old repair to damaged cast iron I-section stanchion
(Picture: Michael Bussell)

Illustration 256 Dockyard Transit Shed, Victoria Dock, Dundee (1874) (Picture: Historic Scotland)

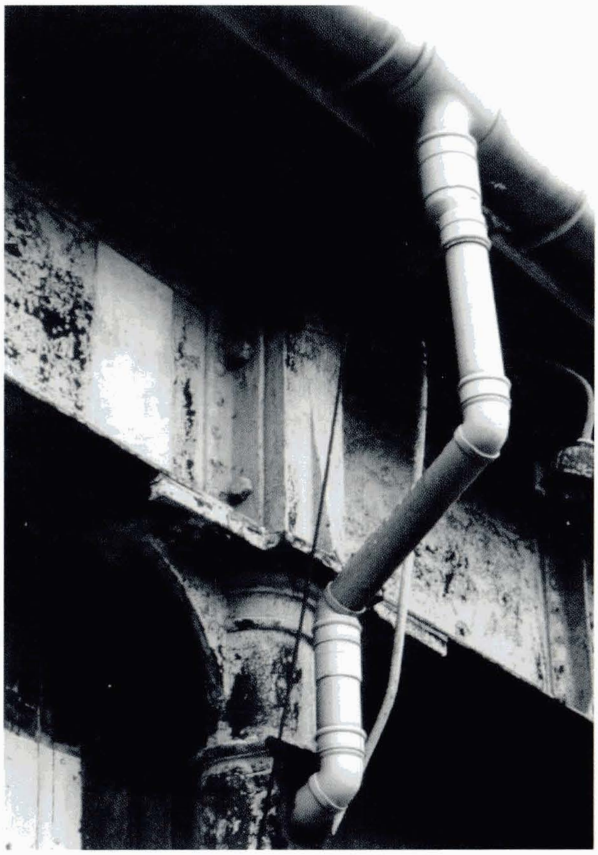


Illustration 257 Dockyard Transit Shed, Victoria Dock, Dundee (1874) Rainwater hopper with decorative casting removed (but kept safe!) (Picture: T. Swailes)

has yet to be proven. A high standard of workmanship is essential for success and the detection of faulty workmanship is likely to be difficult (McGrath, 1999). Great care must be taken in following the manufacturer's specifications for surface preparation, application of the reinforcement and subsequent curing. The work is to some degree sensitive at all these stages to environmental temperature and humidity. The fire resistance of such systems is very poor.

The visual impact of CFRP was trialled recently, as soffit reinforcement and wrapping for a cast iron beam and column respectively, at the 1797 former flax mill in Ditherington, Shrewsbury. Although the trial was not followed through, the technique may prove useful in some buildings as a strengthening measure, but only where the added strength is not required in the event of a fire.

To ensure compliance with the disproportionate collapse requirements of the Building Regulations, the robustness of multi-storey cast iron framed fireproof buildings with brick arch floors may sometimes need to be improved. In such cases, the recommended solution is to provide a lightweight reinforced concrete structural topping (see Section 7.3.2) rather than beam soffit reinforcement.

8.7 Hot repairs

8.7.1 Wrought iron

Repair or strengthening work may involve the use of fusion welding to join pieces of wrought iron or to join steel to wrought iron. This is a job for skilled specialists. Few problems should be encountered in welding high quality wrought iron with low carbon and sulphur content, typically < 0.035% C, < 0.02% S, and with very thin and well distributed slag 'stringers' or 'threads' (TWI, 2001). The greater slag content of poorer quality wrought iron, the result of less complete mechanical working, makes welding more difficult as large slag inclusions may form in the weld. Weldability can be determined by chemical analysis in combination with the examination of micro-sections to determine the distribution and volume of slag.

Site welding of structural work is perfectly possible, provided that the welders are properly trained and qualified to work on wrought iron. Care must be taken in the choice of weld metal and welding technique and, for positional work on site, manual metal arc welding will generally be preferred (Watkinson, 1965). Excessive penetration of the weld into the parent plate should be avoided to reduce the risk of slag inclusions in the weld metal. High sulphur content can also lead to cracking at the grain boundaries of the heat-affected zone, the extent of which can be limited by the use of small diameter electrodes. In the early 1980s, Brolit Welding Ltd used rutile type electrodes of 2.5mm to 3.25mm diameter for the repair and strengthening of the roof to Manchester Central Railway Station (Brolit, 1985). Prior to the refurbishment of this magnificent building as the Greater Manchester Exhibition Centre, there were serious concerns that the wrought iron roof had deteriorated beyond the point of economic repair.

Welding procedure tests should be carried out for structural work and it may be prudent to seek specialist advice at an early stage. For the repair in the 1960s of the corroded wrought iron roof to Aldgate Station on London's Metropolitan and Circle lines, 8" x ½" steel reinforcing plates were welded to the twin wrought iron angles that formed the bottom chord of the roof trusses (Squires, 1968). The work was completed without interruption to the railway traffic passing below. Trials made by The Welding Institute on a sample of wrought iron removed from the roof determined the best techniques and choice of electrodes for the work. Before fillet welding, the corroded edges of the wrought iron angles were ground back to sound metal, with any surface contamination in the weld area removed by flame cleaning and/or wire brushing.

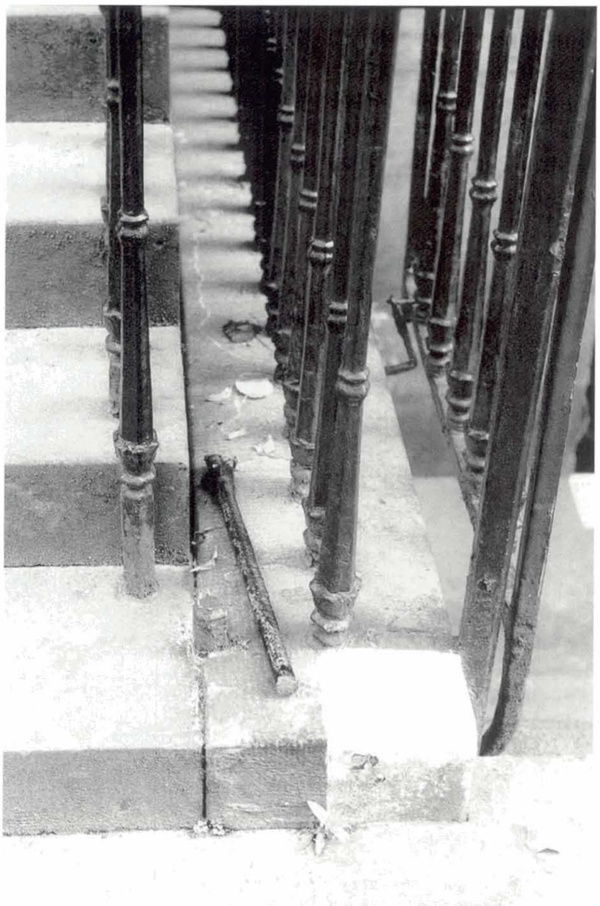


Illustration 258 Broken railings in Edinburgh (Picture: T. Swailes)

8.7.2 Cast iron

For grey cast iron, repair by fusion welding is possible, but because of the brittleness of the material, tolerance to thermal contraction is low and other joining techniques will generally be considered first. Welding of cast iron is a specialist activity, used primarily in mechanical engineering applications where processes can be very tightly controlled, and where the whole of a component to be welded can be pre-heated (Rees, 1999). In the restoration of the 1802 Stratfield Saye Bridge, cracked elements too small in section to be stitched without excessive loss of strength were successfully welded. The pieces were removed from site and the welding carried out under carefully controlled conditions.

For cast iron, manual metal arc welding with graphite coated nickel-based small diameter welding rods and with appropriate pre-heating is the most widely used method. Oxy-acetylene welding provides a reliable way of depositing cast iron filler materials of softness compatible with the parent metal, but is very slow and leads to large thermal contraction strains because of the

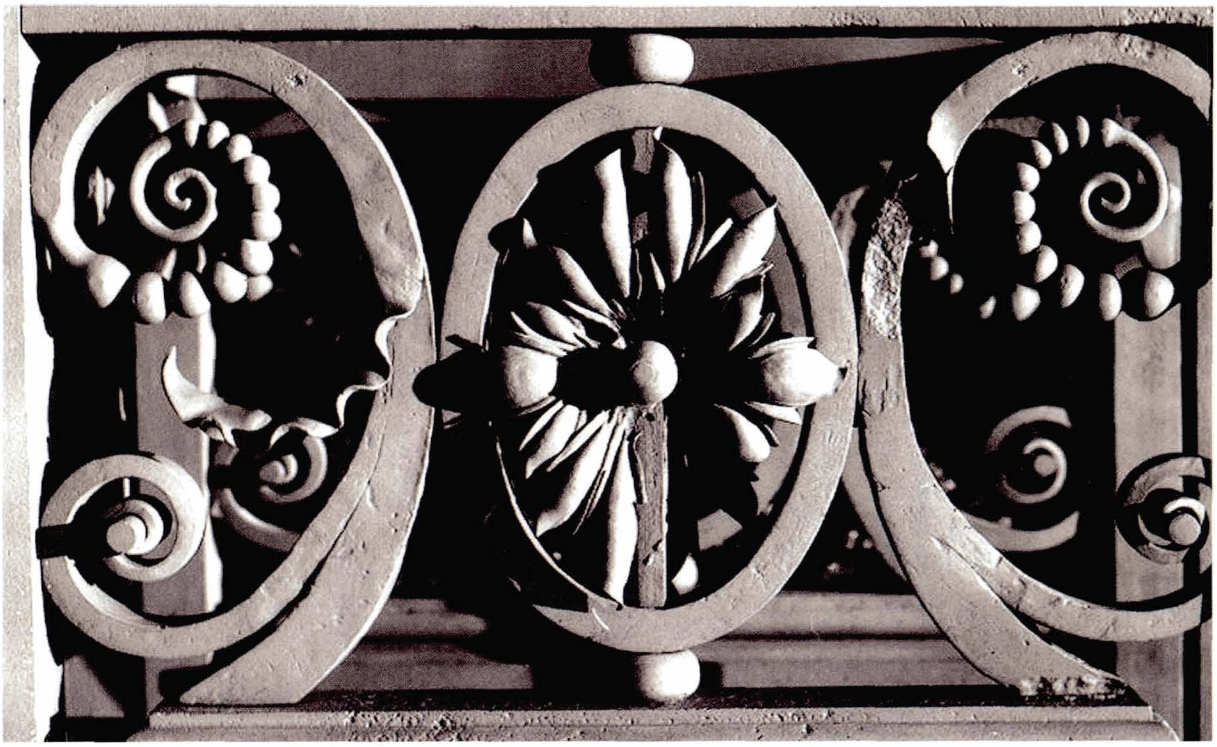


Illustration 259 Gate pier of cast iron with wrought iron flourishes, Thoresby Hall, Newark (Picture: T. Swailes) After cleaning and prior to conservation by Heritage Engineering, The Industrial Heritage Co. Ltd

Illustration 260 Replication of missing cast iron fragments using a 'pattern' of vinyl rubber backed with plaster (Picture: Dorothea Restorations Ltd)

large volume of metal heated. For non-structural applications, or where high strength is not essential, non-fusion welding or brazing using bronze-based alloys has proved successful.

8.8 Filling and jointing materials

A variety of compounds were used in the nineteenth century for filling surface casting flaws (Calvert, 1874-79). One recipe for filler for 'small defects in iron castings' was to fuse nine parts of lead with one of antimony and one of bismuth to form 'an alloy that expands on cooling, and will keep its place'. For modern cosmetic repairs, epoxy-based metal filler may be used prior to repainting. Portland cement or cement mortar is unsuitable as a filling material for ironwork, as it is porous and liable to shrink relative to the iron, thus providing a path for water penetration.

In structural castings in particular, cracks or large surface voids that may weaken an element significantly may be exposed during cleaning for repainting. An advantage of stripping components down to the bare metal is that hidden defects and poorly carried out past repairs will be exposed. A structural inspection of cleaned elements should be made prior to making good defects. Wide gaps between casting joints or cracks within castings may be the result of thermal or structural movements. Filling with inflexible material (or cold stitching) may be inappropriate unless the cause of the defect has been identified and eliminated. Movement joints (sometimes designed and at other times coincidental) are necessary for the effective performance of most iron structures.

Gaps in bolted joints between castings were often filled with a material called 'rust-cement' or 'iron-cement'. One unappealing recipe was 'two parts sal-ammoniac, one part flour of sulphur and 200 parts iron borings, made to a paste with water or old urine'. Sometimes such materials are found together with wrought iron wedges or packing pieces. Hardwood packings and wedges have been found on several occasions during the dismantling of cast iron bridges and cast iron framed buildings.

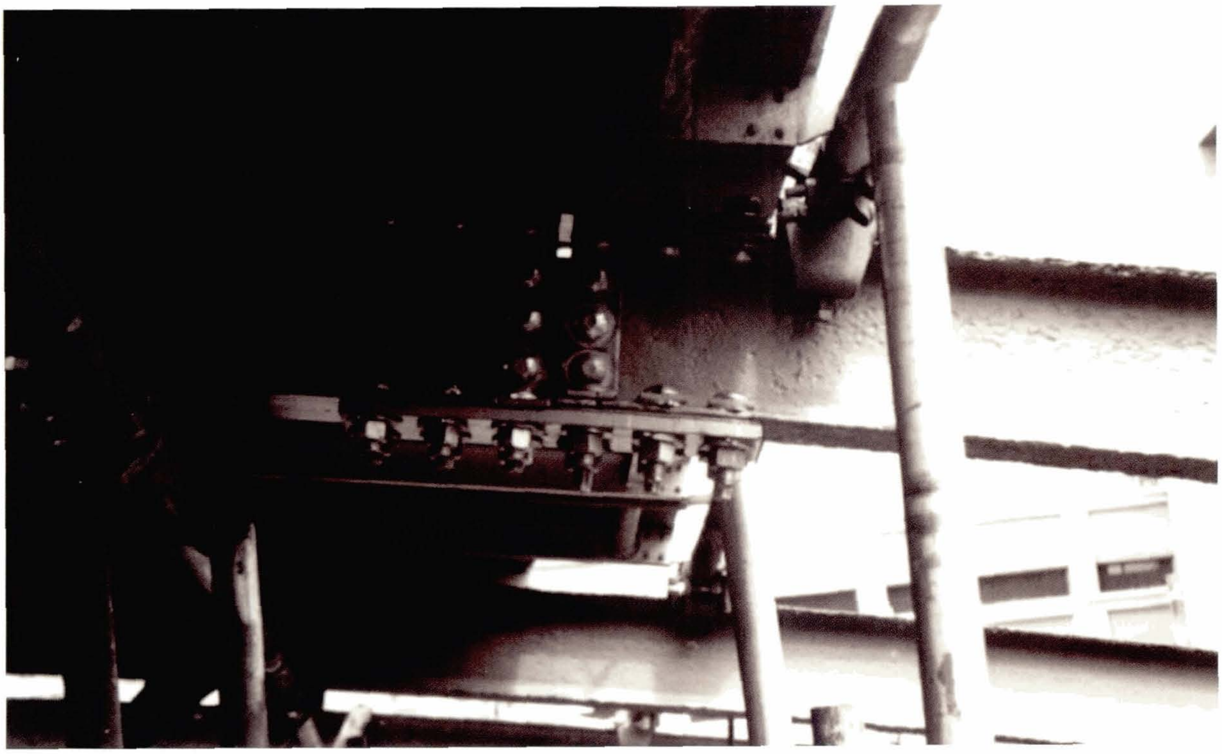


Illustration 261 Queen Street Station, Glasgow: Main train shed roof (1880)
A bolted splice connection forming part of repairs near the apex of the roof (Picture: Network Rail)

Water tanks were generally made up of flanged cast iron panels, bolted together. One form of waterproof joint was exposed during an investigation of the Perth Water Works cistern, now forming the upper storey of the Fergusson Gallery (Allen, Gordon & Co., 2001). The original panel joints contained sealing strips of leather (treated for waterproofing purposes with some kind of organic compound) and wrought iron packing strips. Corrosion and expansion of the wrought iron packing had caused cracking of many of the cast iron panel flanges and failure of several of the wrought iron fixing bolts.

8.9 Replacement of elements or missing pieces

A piece of structural or architectural ironwork one or two hundred years old may be expected to show the effects of wear, corrosion and weathering, and perhaps some bits will be damaged or missing. Architectural cast iron in heavily trafficked areas is vulnerable to damage, and damage is far more easily caused than repaired (Illustration 258). Sometimes vulnerable decorative pieces may be temporarily removed to keep them safe (Illustrations 256 & 257). Provided that the element is safe and serviceable, conservation should generally be carried out with the aim of preventing further degradation, without removing the 'patina of age' (Illustration 259).

Repair is always preferred to replication. However, it may not be possible to make an unobtrusive repair that is structurally efficient. In some cases replacement rather than repair of a damaged component will have to be considered. It may be acceptable to replace missing or broken elements in a kit of parts, provided that some original intact examples remain. Where pieces are broken off a casting they should be retained, either for re-attachment if possible, or as patterns from which satisfactory replacements can be made. Where small pieces are lost, replication of similar surviving pieces may be possible (Illustration 260). Prevention is better than cure, and items such as cast iron railings should be protected against impact damage during building works.

Cast iron railings are made in panels and although the repair of a single damaged baluster by drilling and tapping components together may not be very satisfactory, minor damage does not justify the casting of a replacement panel. Drilled and tapped balusters or baluster panels may be fixed to a capping rail using countersunk stainless steel fixings (Catt, 1995). Galvanised fixings are not recommended for cast iron as bi-metallic corrosion will result.

Unless there is very good reason for not doing so, materials should be replaced like for like. New castings moulded in green sand from well made wooden patterns can give a surface finish and fine detail as good as that achieved by Scotland's eighteenth and nineteenth century architectural ironwork foundries. Each foundry has a preferred mix or recipe

Illustration 262 Broken cast iron railings (Picture: T. Swailes)

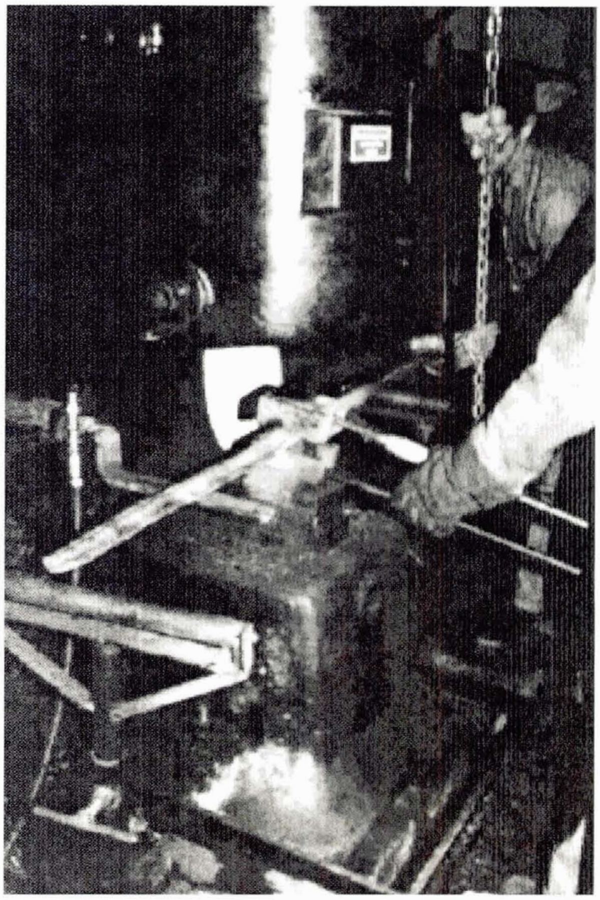


Illustration 264 Forging of wrought iron glazing bars (Picture: Dorothea Restorations Ltd)

Illustration 263 Welded repairs to wrought iron glazing bar ends (Picture: Heritage Engineering Ltd)

for different types of casting, including decorative work and, because the raw materials are better understood, modern grey cast iron is generally superior in terms of material strength to any made in the nineteenth century. Poor workmanship at the foundry can result in poor castings being made from superior materials and a good casting will be generally free from surface blowholes or scabs and require little 'fettling' prior to painting. If possible, the opportunity should be taken to examine castings at the foundry prior to their being painted. The ownership of patterns should be agreed at the outset between the client and the foundry as patterns are expensive and may retain a value once the work for which they were made has been completed.

Occasionally, safety reasons may be cited as justification for the comprehensive replacement of original parts using superior modern materials. An example is the upgrading of the solid cast iron parapets at North Bridge Edinburgh, over Waverley Station. Here the panels were recast in spheroidal graphite (SG) cast iron, for greater ductility and to cover new steel vehicle restraints. For the ornate cast iron parapets to Cleveland Bridge in Bath a solution was found that

Illustration 265 Skelmorlie Castle, Largs: garden conservatory (c.1860) Severe corrosion at the lower bearing of a wrought iron rib. Note that the supporting cast iron member remains in good condition (Picture: T. Swailes)

Illustration 266 Skelmorlie Castle, Largs: garden conservatory (c.1860) Curved wrought iron ribs to the roof comprise strip riveted to the sides of rectangular bar, as a bearing for the glazing. With the glazing incomplete, the detail traps water (Picture: T. Swailes)

Illustration 267 Kingsknowe Hotel conservatory Decorative cast iron facing panel. The panels conceal the timber and iron posts within the conservatory walls (Picture: T. Swailes)

Illustration 268 Kingsknowe Hotel conservatory Damage to cast iron facing panel. Water can penetrate to the rear face of the panel, which is inaccessible for cleaning and painting. Water ingress is also likely to lead to deterioration of the timber elements (Picture: T. Swailes)

enabled the original material to be retained. Raised kerbs were provided to the sides of the road crossing the bridge, profiled to deflect vehicles away from the pavement and the parapets.

Replacement in steel may be regretted afterwards. Elements of Craigellachie Bridge were replaced with structural steelwork in 1963, only for the whole bridge to be by-passed a decade later. Aside from any visual impact, replacement of original parts of an iron structure involves the loss of information on the original methods and materials of construction, including metallurgical properties and early techniques of metal working and jointing. Where replacement is unavoidable and has been approved, details of the affected parts of the structure should be comprehensively recorded before work is carried out and also while connection details are revealed during any dismantling work. Where use of original materials is not possible, the aim should be to carry out a well-detailed 'honest' repair or replacement, in which modern materials and methods blend with the original structure, while being distinguishable from it (Illustration 261).

Periodic replacement of components on an extensive scale leads to difficult questions about the authenticity of a historic structure. The Palm House in Kew Gardens is an interesting case which illustrates shifting attitudes and practices in conservation over the last 50 years (Minter, 1990). The building was neglected during the Second World War and closed to the public in 1952 after an unfavourable engineer's report recommended replacement with a new structure. Good sense prevailed, the glass was removed, and the ironwork was taken back to bare metal and defects made good. Some original wrought iron glazing bars were replaced with galvanised steel sections. For re-glazing, green-tinted glass sheets in 3' lengths were used, these being a near-match to the original cylinder glass supplied by Chance & Co. of Birmingham. Although painted inside and out at regular intervals after the 1950s restoration, thirty years later the structure was again in poor condition. From 1985 to 1989 the building was dismantled, and a large number of corroded and damaged parts replaced or repaired prior to re-assembly. For this restoration, more extensive use was made of new materials. The original wrought iron glazing bars were replaced with stainless steel extrusions, the earlier restoration of the Belfast Palm House having set a precedent with the use of extruded mild steel bars. Modern toughened glass was used to glaze some areas and annealed glass was used elsewhere. Quite a number of the original cast iron and the larger wrought iron structural sections were replaced in ductile or spheroidal graphite (SG) cast iron.

More recently, recycled original materials have been used in glasshouse restorations. For the glasshouse at Glasnevin, Dublin (which like the Kew Palm House was constructed by Richard Turner) a forging process was developed by Dorothea Restorations Ltd to enable twenty different glazing bar profiles to be replicated in recycled wrought iron (Illustration 264). For the restoration of Glasgow's Tollcross Winter Gardens, The Industrial Heritage Co, replaced the heavily corroded lower bearing ends of the wrought iron glazing bars by welding on wrought iron sections of matching profile (Illustration 263). Much more of the original fabric has been retained than was the case with the Palm House at Kew, in the interests of authenticity. To make rolls to match existing sections is expensive, but the Real Wrought Iron Co. in North Yorkshire rolls old wrought iron into square, round and flat bars and undertakes to match any existing section (Topp, 2001). In every case, it is advisable to agree the approach to be taken either by means of an agreed conservation plan or by prior discussion with the relevant Conservation Officer or Historic Buildings Inspector.

The replacement of bolts or rivets that have lost a significant part of their cross-section as a result of corrosion may sometimes be necessary. Provided their details are recorded, and that some examples of the original fixings can be retained on the structure, replacement is likely to be acceptable. By virtue of their hand-crafted nature, reflecting local traditions, blacksmith's forgings will merit greater care in their conservation than will mass-produced fixings.

If as part of a refurbishment project other corrosion-resistant metals are used alongside iron or steel, such as stainless steel or aluminium, the abutting surfaces must be isolated electrically (see Section 8.7.1). Neoprene isolating washers or epoxy bedding materials may be used for this purpose (Gibbs, 2000; Wallis, 1999).

8.10 Corrosion and corrosion prevention

8.10.1 Corrosion

Iron rusts or corrodes in the presence of oxygen and water, reverting to the natural oxide forms of the iron ores from which it was extracted. Corrosion is generally prevented by the application of surface coatings designed to keep the iron dry.

Water borne products of the corrosion of iron or steel may be deposited as reddish-brown rust stains. Below ironwork bearings or joints in buildings such staining is a sign of past leaks and a pointer to areas that require inspection. Rust should be removed and paintwork made good as soon as signs of wear and tear are noticed. In roof structures, the lower parts of rafters or glazing bars are particularly vulnerable (Illustration 265). Ironwork details that work well in a dry, well-maintained building can be the seat of corrosion related problems when water is allowed in (Illustration 266).

Unchecked, corrosion will progressively eat away the metal beneath permeable outer layers of rust. As corrosion continues, the products of corrosion expand to occupy a volume many times greater than the original metal. Where wrought-iron is built-in to masonry and the expansion associated with corrosion is restrained, the resulting bursting forces may split the masonry units or 'jack' apart the joints into which the ironwork is embedded. Cracking of cast iron decorative elements is quite often corrosion-related (Illustrations 267 and 268).

Cast iron has far better natural corrosion resistance than wrought iron, which in turn is a little more resistant to corrosion than modern mild steel. Loss of cross-section due to corrosion is generally more significant, also rolled wrought iron and steel sections

Illustration 269 Queen Street Station, Glasgow: Main train shed roof (1880) The roof from above, the temporary covering and containment structure for removal of lead-based paints at one end. (Picture: Network Rail)

as they are thin compared to cast iron sections. Even in the early twentieth century, cast iron beams were being used despite the weakness of the material in tension. As one writer put it, 'no kind of girder is so suited for damp basements and similar situations, or as proof against atmospheric changes, as the cast iron' (Dawnay, 1901). In the mid-nineteenth century, it was believed that a thin film of iron silicate formed a protective layer on the surface of a casting when the molten iron reacted chemically with the moulding sand.

Cast iron is generally resistant to atmospheric corrosion. Even where the ends of cast iron beams have been embedded for many years in damp masonry, the loss of section or corrosion-related expansion is usually insignificant. The condition of the bearings of wrought iron or steel beams on the other hand requires careful investigation.

There is a long tradition in the use of cast iron for quality rainwater goods, such as hoppers, down-pipes and gutters. In some cases components serve a dual role, both as part of the rainwater disposal system for a building and as structural supports. Cast iron water pipes deteriorate over time as a result of graphitisation, a form of corrosion that does not require the presence of oxygen. The products of internal corrosion are continually removed from the inside of the pipe by flowing water, leaving behind only a 'skeleton' composed mainly of graphite. There is no loss or increase in section, although a very considerable thickness of cast iron may have been 'converted' and have negligible mechanical strength. When cast iron columns have also served as rainwater down-pipes, the taking of cores from the column walls to check the extent of graphitisation is recommended.

Corrosion of iron in air is increased by some atmospheric pollutants and, in a marine environment, by the presence of salts. Pollutant or salt particles may act as centres from which uneven corrosion pitting develops. Splash or spray zones, subject to repeated wetting and drying, are affected worst of all. Coastal structures suffer from wear due to the movement of shingle beaches and, at higher levels, due to wind blown sand (Bateman, 1999). In such aggressive environments, the wear resistance of the corrosion protection system is crucial.

Soil, masonry, mortar, concrete of uncertain composition, and other materials that may be in contact with iron, may contain a variety of corrosive agents. Opening up of representative vulnerable areas for inspection and sampling for chemical analysis of the materials surrounding the iron may be required.

The terms electrochemical or galvanic corrosion are used to describe increased corrosion arising from contact between dissimilar metals, or in some instances, two pieces of the same metal. When iron is in contact with a metal which is electrochemically less reactive, such as copper, its rate of corrosion in the presence of oxygen and water will increase. The effect will be greatest if the iron parts of the structure are small in size compared to the copper parts, as with iron rivets to copper sheathing, for example.

8.10.2 Original corrosion prevention systems and finishes

Traditional and most modern paint systems consist of a primer, undercoat, and topcoat. The primer provides a good key to the metal surface, the undercoat acts as a barrier to the penetration of moisture and air and the topcoat seals the surface and provides a decorative finish (Ashurst, 1988). The characteristics of existing paint layers must be determined before they are disturbed as part of any repainting work. Red lead (bright orange when first exposed by scraping) is the most effective of the traditional primers. It is an effective rust inhibitor, but it is toxic, as are other lead-based paints that were used in the past (see Section 8.7.4). From the mid-nineteenth century, iron oxide primers came into wide use, particularly for engineered structures (Matheson, 1873). Although red oxide primer does not act as a rust inhibitor, it was much cheaper and less heavy than red lead, and it adheres very well to iron.

For sheet iron cladding, zinc galvanising was used to provide additional protection after patents were taken out in the late 1830s by H Crawford (Warren, 1970). The 1847 catalogue of a Birmingham based manufacturer of corrugated iron roofs and buildings, many destined for export to British colonies, gave some details of alternative finishes then in use for corrugated iron roofing (Porter, 1847). Galvanising was a little more expensive than the alternatives of three coats of 'the patent white of zinc' or 'the oxide of iron'. By 1855, atmospheric pollution had caused the failure of several galvanised railway station roofs in the North of England, though ship-building slip roofs in Pembroke Dockyard were reported to be in good condition after 10 years service, despite their coastal location (Phillips, 1855).

Seaside piers required wear-resistant coatings. Cast iron columns were made oversize to allow for loss of material due to wear and may have to be protected and strengthened by concrete encasement at beach level (Bateman, 1999). Deck level pier ironwork was traditionally protected with thick, lead-based primers with thicker pitch finishes, applied hot.

Until fairly recently, the protection of external ironwork against corrosion generally involved localised repairs and over-painting. However, it is possible that what is found on the lowest layer in a paint scrape may not be original, but what was applied after an earlier episode of cleaning down to bare metal.

Analysis of the layers of paint on an iron structure may form part of an archaeological investigation that enables an earlier colour scheme to be re-created. In some cases, great care was taken in choosing the finish for an iron structure and archive research may prove rewarding. The artist Owen Jones devised a subtle colour scheme for the ironwork in the building for the Great Exhibition of 1851 that was designed to enhance perspective and emphasise the vastness of the interior. For the roof to St. Pancras Railway Station, W H Barlow opted for a muddy brown colour (found recently under more than 50 separate paint layers), deflecting criticism with the comment that it would not show the soot. Examination of paint layers on iron railings in Glasgow's West End has shown that often the original finish was a dark blue-green, also known as 'invisible green', with the now more usual black becoming popular only later in the nineteenth century. Restoration of original colour schemes will not always be appropriate. In the terraces of Edinburgh New Town, black is now universal for railings, thus avoiding variation in the shade of green that might otherwise be adopted.

Earlier re-paintings may themselves be of historical interest. A scrape of the Magdalen Green Bandstand, Dundee, revealed what appeared to be camouflage paint. Perhaps the structure served as a wartime lookout post on the banks of the Tay? Cheerful colours were selected for the 1990 restoration in keeping with other surviving examples of brightly painted Victorian ironwork (see Illustrations 2, 3 and 4).

8.10.3 Maintenance of existing paintwork

Repainting of exposed ironwork as a regular maintenance task does not involve the wholesale removal of existing coats of paint. Sound areas of paint may simply be abrasive cleaned to receive a topcoat, paying attention to Health and Safety precautions outlined in Section 8.7.4. For minor areas of damage, preparation involves the removal of rust, including corrosion beneath paint layers, and unsound loose or cracked paint. The surface is then primed before rust can re-form and then suitable undercoats and the topcoat are applied.

Over-coating of paint layers is not always the best solution in the long term. Paint that has been built up in many layers to a considerable thickness is particularly prone to chipping. Relatively large areas around the damage may need to be rubbed down to visually blend in the newly repainted areas with the old. Very thick layers of paint that blunt the decorative features of a casting or obscure the details in intricate forged work should be stripped back. Determining the soundness of existing paint layers and the limits of local corrosion can be difficult. Corrosion spreads outwards beneath a paint surface from areas of local damage. Painting contractors and paint suppliers are therefore understandably reluctant to guarantee their workmanship or materials when surface preparation does not involve removal of all existing coatings. Finally, stripping down to bare metal exposes any defects and past repairs for inspection and remedial action, prior to repainting.

Nonetheless, in view of the potential future interest in the historic paint schemes applied, and as the documentation relating to any paint scrapes may be mislaid, at least a small area of historic paintwork should be kept in an unobtrusive location as a physical record of earlier corrosion protection systems and their maintenance.

Before privatisation, British Rail policy was to examine the condition of all its structures at six-yearly intervals. For a railway station roof this involved inspection from

Illustration 270 Queen Street Station, Glasgow: Main train shed roof (1880)
Access maintained for railway passengers at platform level (Picture: Network Rail)

platform level. Access provision for painting at twelve yearly intervals enabled closer inspection of less accessible areas (Connell, 1993). In such circumstances, where access for maintenance is difficult and expensive, a paint system with a long life to first maintenance will be appropriate.

8.10.4 Cleaning, surface preparation and paint specifications

The preparation of surfaces to receive paint is of paramount importance. When stripping down to bare metal, contaminants to be removed before painting are rust, water-soluble corrosion salts, loose mill scale (but not sound mill scale), old paint, and oil or grease. Mill scale is a brittle, non-metallic skin of oxide on the surface of rolled steel or wrought iron sections, formed on cooling after passing through the mill rolls. It acts as a corrosion resistant layer, as does the surface skin on iron castings formed by fusion of the moulding sand in direct contact with the molten iron. Manual surface cleaning by scraping and brushing is not the most efficient method but may sometimes be the only practical option. When surface preparation is less than perfect, a modern rust inhibiting primer such as zinc phosphate may be preferred. Most paints will not adhere to a damp surface and newly applied paint will be damaged by exposure to a humid atmosphere, so painting outdoors should not be programmed for the winter months.

Legislation now prevents the sale of lead-based primers to the general public and testing of existing ironwork surfaces is needed to establish the presence of lead-based paints (BCF, 1998). However, special permission can be obtained for the use of lead-based paints for the repair of Category A-listed buildings. In such cases, the paint supplier will obtain confirmation of the status of the structure from Historic Scotland. Lead particles can be breathed in or swallowed as paint chips, or in contaminated dirt or water, with very serious health consequences.

Where lead-based paints are to be removed, very careful planning, control and monitoring is required to ensure the Health and Safety of operatives, users of the building and the public. The main train shed roof to Glasgow's Queen Street Station was encapsulated during recent refurbishment works to enable lead pollutants to be contained and disposed of safely, while allowing the platforms below to remain in use (Illustrations 269 and 270).

For the refurbishment of the People's Palace Winter Gardens in Glasgow, following a fire in early 1998, a temporary containment structure was constructed for abrasive blast cleaning of the iron and steelwork (Glasgow City Council, 2000). Smoke tests were carried out to ensure that a 100% seal was achieved. All personnel within the containment structure wore protective suits and breathing apparatus and lead levels in their blood were monitored. The air quality inside and outside the containment structure was also tested periodically while cleaning was taking place. Great care was taken with the containment and safe disposal of the waste arising from the cleaning operations (Illustrations 271 & 272).

For smaller buildings, the hazards associated with lead-based paints may be removed from site by dismantling the structure. The separate parts can be cleaned, repaired, and repainted in a factory or workshop, where the risks to health may be more economically managed. Immersion in a bath of dilute sulphuric or phosphoric acid is then an effective method for the removal of rust and loose mill scale.

Standard specifications for surface cleanliness and roughness for steelwork should not be used indiscriminately for decorative wrought or cast iron. Wrought iron is softer than steel and heavy-handed grit blasting will remove protective mill scale. For blacksmith's work, flame cleaning may be used provided that the fire risk can be contained. Care must be taken with thinner parts that may distort when heated. Applying heat is also an effective way of loosening rust, as rust expands differentially with respect to iron, and can then be brushed, knocked or shaken off. Probably the least damaging method of cleaning fine wrought iron work is with a proprietary chemical paint stripper, followed by steam cleaning (Topp, 2001). Cleaning of ironwork after applying a chemical paint remover and before applying paint is essential. For castings, the protective skin left by green sand moulding can withstand careful blast cleaning. However, over-aggressive blast cleaning can remove sound caulking and jointing materials, which will then need to be replaced. Blast cleaning of cast iron should use a chemically inert abrasive at low pressure. For fine decorative cast iron work, nylon beads have been successfully used as an abrasive (D S Mitchell, 2001).

Selection of a paint system for an iron structure must take into account the conditions of exposure and the planned frequency of maintenance, which will in turn depend on ease of access. For decorative ironwork, which may be viewed close-up, the overall paint thickness must not be too great. The method of surface preparation and the choice of primer may vary for cast iron, wrought iron, and steel. For the subsequent paint layers it is compatibility with the primer, or with each other, that is important.

Some specialists in the restoration of architectural cast ironwork dislike the more viscous epoxy based paint systems as they tend to obscure fine details (D S Mitchell, 2001). Such systems are also considered by

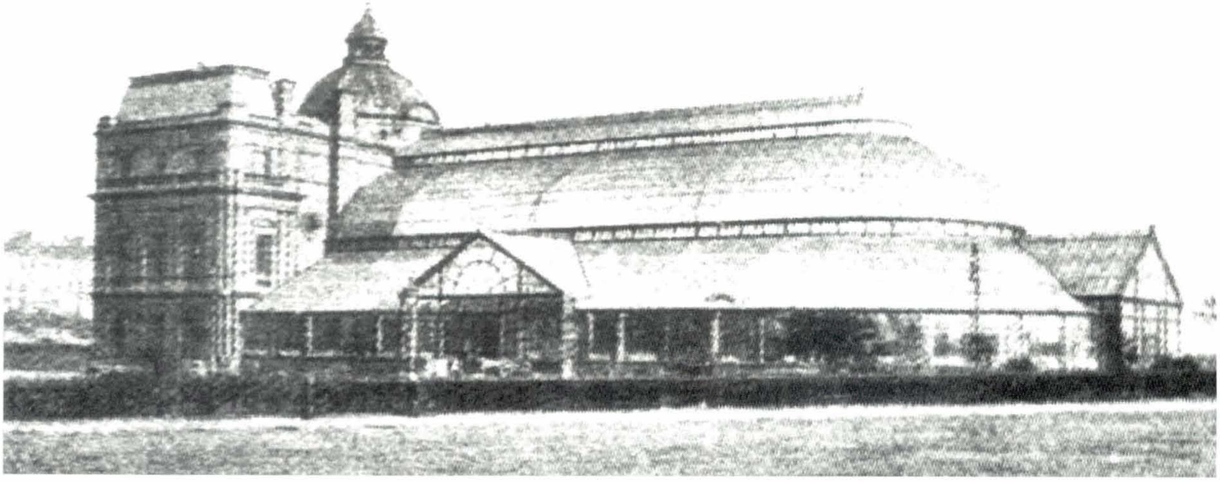


Illustration 271 The People's Palace, Glasgow Green, Glasgow: The Winter Garden (1899) An early twentieth century view (Picture: Glasgow City Council)

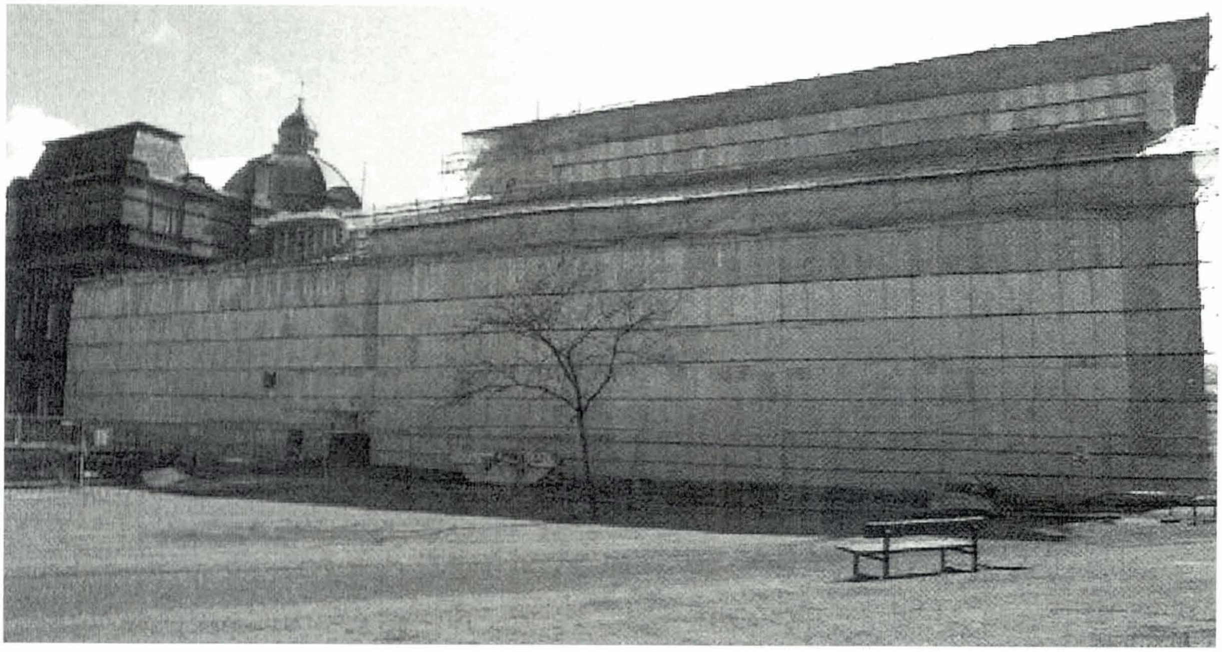


Illustration 272 The People's Palace, Glasgow Green, Glasgow: The Winter Garden (1899) Temporary containment structure (Picture: Glasgow City Council)

some to create a hard shell coat not entirely compatible with the porous cast iron beneath, unlike more traditional paint systems. For external cast ironwork, a five coat system has proven satisfactory, with a zinc phosphate primer, an intermediate coat of micaceous iron oxide (MIO) and gloss finish coats. A four coat system used with success for decorative wrought ironwork begins with a zinc phosphate anti-corrosive primer, followed by a micaceous oxide intermediate coat, then two finishing coats applied by brush or spray. For fine external wrought ironwork in particular, great emphasis is placed on, after initial repair or restoration, 'annual inspection, both rigorous and minute, of every detail of ironwork' (Topp, 2001). Problems should be attended to at the first opportunity, low-viscosity oil based rust inhibitor may be injected into joints as a temporary measure, and re-painting should be carried out at no more than five-yearly intervals.

For larger engineering structures and parts of buildings with poorer access for maintenance, the emphasis will be on life to first maintenance rather than the retention of fine detail. The ironwork to the Winter Garden at the People's Palace was cleaned by abrasive blasting to a standard better than Sa2½, in accordance with BS4232, with BS7079 used as the standard to judge cleanliness. The following paint system was used: 1 coat 2 pack epoxy zinc phosphate primer (100 micron dry film thickness), 1 coat 2 pack epoxy high build (100 micron dry film thickness), and 1 coat 2 pack quick drying acrylic urethane gloss (40 micron dry film thickness). The specification required that the white gloss paint should have a 15 year life to first repair.

Unpainted, cast iron can last indefinitely in a benign environment. It was decided not to paint the girders of Braid Burn Bridge, Duddingston, as part of the bridge's conservation (Illustration 127).

9 SOURCES OF INFORMATION AND ADVICE (As at March 2006)

9.1 Introduction

The contact details of public and private organisations that collectively provide information and advice on any aspect of historic iron structures in Scotland are given below. Many of the sources listed have proved useful in the preparation of this Practitioners' Guide. Each sub-section alphabetically lists organisations in Scotland, followed by organisations outside Scotland. Some sources are not easily categorised. For example, the best civil engineering library in Britain is kept by the Institution of Civil Engineers, so it appears with the listing for that organisation under the heading 'Professional institutions and accreditation bodies', rather than under 'Libraries, archives and information services'.

Web links are given to 'on line' Internet resources, the scope and usefulness of which is likely to increase greatly over the next few years. Now, archive material can generally be located over the Internet, but in future more printed and manuscript materials will be digitised, for remote viewing. It is already possible, for example, to view freely on line and at high resolution the will of the Scottish civil engineer Thomas Telford (via SCAN's site scottishdocuments.com) or the architectural drawings for Edinburgh's McEwan Hall and its iron and steel framing (via 'The Drawn Evidence').

Where specialist services and materials are noted below, this information is provided in good faith but the inclusion of any particular firm, individual or product does not imply endorsement by the author of this Practioners' Guide or by Historic Scotland.

9.2 Government and its agencies

The Health and Safety Executive (HSE)

Belford House, 59 Belford Road,
Edinburgh, EH4 3UE

Tel 0131 247 2000
Fax 0131 247 2121

375 West George Street, Glasgow, G2 4LW

Tel 0141 275 3000
Fax 0141 275 3100
Web http://www.hse.gov.uk

The mission of HSE is to ensure that risks to people's health and safety from work activities are properly controlled. In 2002, one or two construction industry workers were dying at work every week. The industry targets were to reduce the fatal and major injury rate by 40% in 2005 and by 66% in 2010 but it seems unlikely that these targets will be achieved. Ignorance of good practice is no defence in a court of law. Many HSE publications that relate to construction safety may be downloaded as *.pdf files from the web site, at

http://www.hse.gov.uk/pubns/conindex.htm

These publications include leaflets that explain the duties and role of the Client, the Planning Supervisor, the Designer and the Contractor under the Construction Design and Management Regulations. Other free on-line publications relate to noise, chemicals and hazardous substances, safety inspection requirements, fire safety, safety in excavations, personal protective equipment, working at height and site welfare facilities. HSE Bookfinder is an on-line catalogue to priced and free HSE printed publications at

http://www.hsebooks.co.uk/

Hsedirect, at www.hsedirect.com is a subscription on-line information service providing access to health and safety legislation and guidance. Within hsedirect, 'COSHH Essentials' is a free aid developed to help firms comply with the Control of Substances Hazardous to Health Regulations (COSHH).

Historic Scotland

Longmore House, Salisbury Place,
Edinburgh, EH9 1SH

Tel 0131 668 8600
Fax 0131 668 8669
e-mail hs.website@scotland.gsi.gov.uk
Web http://www.historic-scotland.gov.uk/

Historic Scotland is the Agency within the Scottish Executive Education Department that safeguards the nation's built heritage and promotes its understanding and enjoyment. Details of priced and free publications may be obtained on-line.

National Survey of Buildings and Archaeology in Scotland

John Sinclair House, 16 Bernard Terrace
Edinburgh, EH8 9NX

Tel 0131 662 1456
Fax 0131 662 1499
e-mail nmrs@rcahms.gov.uk
Web http://www.rcahms.gov.uk/

The Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS) surveys and records the built heritage of Scotland and makes the results available to the public through the Collections of the National Monuments Record of Scotland (NMRS). A great wealth of information and material is held on the sites, monuments and buildings of Scotland's past.

CANMORE provides on-line access to the database of the National Monuments Record of Scotland (NMRS). The database contains details of many thousands of archaeological sites, monuments, buildings and maritime sites in Scotland together with an index to the drawings, manuscripts and photographs in the Collections of the NMRS. CANMORE enables this data to be searched by location (place name, area or Ordnance Survey 1:10,000 map sheet) by type (the classification or function of a site, monument or building) or by keywords, such as 'iron'. Data relating to the NMRS Architecture Collections is not fully on-line at the time of writing.

The Scottish Executive

Planning and Building
Area 3-H, Victoria Quay, Edinburgh, EH6 6QQ

Tel 0131 244 0763
Fax 0131 244 0785
e-mail (general enquiries) ceu@scotland.gov.uk
Web http://www.scotland.gov.uk/

The Development Department of the Scottish Executive advises Scottish Ministers on planning matters and is responsible for policies on building control. The latest information about Building Standards is available, and copies of the standards themselves may be freely downloaded as *.pdf files, via the Scottish Building Agency Home Page at **http://www.sbsa.gov.uk/**

English Heritage

Customer Services Department
PO Box 569, Swindon, England
SN2 2YP

Tel 0870 333 1181
Fax 0179 341 4926
e-mail mailto:customers@english-heritage.org.uk
Web http://www.english-heritage.org.uk/

CADW: Welsh Historic Monuments

National Assembly for Wales
Cathays Park, Cardiff, Wales, CF10 3NQ

Tel 0292 050 0200
Fax 0292 082 6375
e-mail cadw@wales.gsi.gov.uk.
Web http://www.cadw.wales.gov.uk/

9.3 Museums and Sites

Bonawe Iron Furnace

Situated between the S shores of Loch Etive and the village of Taynuilt, off the A85

(Grid Reference NN010318)

Tel 01866 822432

The most complete remains of charcoal fuelled ironworks in Britain, with displays illustrating iron making. In the care of Historic Scotland, open summers only. Pictured on the Historic Scotland web site, there are also good internal views of the furnace on the undiscovered scotland website:

Web
http://www.undiscoveredscotland.co.uk/taynuilt/bonawe/

Bo'ness and Kinneil Railway

Run by The Scottish Railway Preservation Society (SRPS)
Bo'ness Station, Union Street, Bo'ness
West Lothian, EH51 9AQ

Tel 01506 822298
e-mail enquiries@railway.srps.org.uk
Web http://www.srps.org.uk/

The train shed was relocated from Haymarket, Edinburgh. The Bo'ness Development Trust is working with the SRPS to set up the Scottish Railway Museum, and future building plans include re-erection of one of the 1888 Glasgow International Exhibition buildings (the 'Penman Building') as a display shed at Bo'ness North Yard.

The Dunaskin Open Air Museum
(in liquidation 2005)

Dalmellington Rd, Waterside, Patna, Ayrshire
e-mail dunaskin@btconnect.com
Web http://www.dunaskin.co.uk/

An open-air museum, on the site of the Dalmellington Ironworks, open summers only. Educational material on the web site includes illustrated descriptions of blast furnaces and furnace blowing engines. Currently stores the iron salvaged from the Caird Engine Shop, Arthur Street, Greenock.

East Dunbartonshire Museums

The Auld Kirk Museum, The Cross, Kirkintilloch
Glasgow, G66 1AB

Tel 0141 578 0144
Fax 0141 578 0140
Web
http://www.edunbarton.org.uk/whatson/museums/auld_kirk_museum.htm

Falkirk Museums

Callendar House, Callendar Park, Falkirk, FK1 1YR

Tel 01324 503770
e-mail callendar.house@falkirk.gov.uk

(Illustration 275)

Grangemouth Museum Workshop

7 - 11 Abbotsinch Road, Abbotsinch Industrial Estate
Grangemouth, FK3 9UX

Tel 01324 504689

The collections contain objects from the many iron foundries that were once concentrated in the area, including patterns, tools, machinery and products and also reflect the regional importance of engineering and ship building. Only part of the collection is displayed and viewing of the larger amount of material held at the Grangemouth store is possible by prior appointment. The Archives and History Research Centre at Callendar House hold information on foundries and their products.

National Museums of Scotland

Chambers Street, Edinburgh, EH1 1JF

Tel 0131 247 4422
Fax 0131 220 4819
e-mail
Web http://www.nms.ac.uk/mos/

There are excellent displays relating to iron and steel industries and their products in the Museum of Scotland and the adjoining Royal Museum in Chambers Street.

The Granton Centre

242 West Granton Road, Edinburgh, EH5 1JA

Tel 0131 247 4470
Fax 0131 551 4106

The Granton Centre is the major store for the National Museums of Scotland, holding thousands of objects, including some building and engineering artefacts. Free tours are available.

New Lanark World Heritage Village

New Lanark Conservation Trust, New Lanark Mills
Lanarkshire, Scotland, ML11 9DB

Tel 01555 661345
Fax 01555 665738
(Visitor Centre) e-mail visit@newlanark.org
Web http://www.newlanark.org/

In December 2001 New Lanark became the fourth site in Scotland to be inscribed on UNESCO's World Heritage List. Structural ironwork is splendidly exposed in several buildings in public access areas and cast iron beams from one building have been re-used to support a bridge across the lade.

Scottish Maritime Museum

Harbourside, Irvine, Ayrshire, KA12 8QE

Tel 01294 278 283
Fax 01294 313 211
Web http://www.scottishmaritimemuseum.org/

Includes the relocated cast-iron and timber-framed Linthouse Engine Shop, 1873: the largest building to have been moved in Britain.

Summerlee Heritage Park

Heritage Way, Coatbridge, Lanarkshire, ML5 1QD

Tel 01236 431 261
Fax 01236 440 429
Web http://www.monklands.co.uk/leisure/summerlee.htm

One of Scotland's largest industrial heritage visitor attractions, open all year, on a 22-acre site based around the nineteenth century Summerlee Ironworks. Working machinery is displayed in a large exhibition hall, an 1880s blast furnace is recreated, and reconstructed workshops include a brass foundry and a spade forge.

Amberley Museum

Amberley, Arundel, West Sussex, England, BN18 9LT

Tel 01798 831370
Fax 01798 831831
e -mail office@amberleymuseum.co.uk
Web http://www.amberleymuseum.co.uk/

An open-air museum concerned with the industrial history of south east England. The Paviours Museum of Roads and Road Making, of general interest to the civil engineer, is housed in a pre-fabricated iron building dating from 1842. The museum also holds a major collection relating to concrete and concrete technology.

Beamish:
The North of England Open Air Museum

Beamish, County Durham, England, DH9 0RG

Tel 0191 370 4016 / 0191 370 4022
Fax 0191 370 4001
e-mail museum@beamish.org.uk
Web http://www.beamish.org.uk/digest.htm

The Beamish Photographic Archive houses a collection of over 100,000 historical images from the North East of England dating from the 1860s up to the present day. Also available is a large collection of trade catalogues of suppliers and manufacturers. The catalogues cover everything from kitchen ranges, decorative castings, banners, agricultural implements and tools, sports and pastimes to industrial machinery. The earliest catalogue dates back to c.1825 though the majority of the catalogues date between 1860 and 1960. The archives can be viewed on weekdays by appointment only.

The Black Country Living Museum

Tipton Road, Dudley, West Midlands,
England, DY1 4SQ

Tel 0121 557 9643
Fax 0121 557 4242
e-mail info@bclm.co.uk
Web http://www.bclm.co.uk/

An open air site, covering the working of wrought iron and other manufacturing industries of the Black Country, a region of about 400 square miles to the West of Birmingham. Collections include machinery and products from a local rolling mill and an anchor forge, and material relating to the chain, nail, screw, sheet metalworking and glass making industries. Civil engineering material includes documents relating to the Horsley Bridge Company and the mechanical engineering collection includes steam engines, pumps and boilers. Some of the main exhibition spaces are beneath an impressive cast iron arched roof of 1888, which originally covered swimming baths in Smethwick.

Chiltern Open Air Museum

Newland Park, Gorelands Lane, Chalfont St. Giles
Bucks, England, HP8 4AB

Tel 01494 871117
e-mail coamuseum@netscape.net
Web http://www.coam.org.uk/

Among over 30 re-erected historic buildings are two small iron structures, both from Walter MacFarlane's Saracen Foundry: a public convenience made in 1906 for a tramway terminus and a 1950s telephone kiosk. A third prefabricated building dating from 1886, timber framed and clad in corrugated iron, is a typical example of the churches and mission rooms erected in the UK in the nineteenth century and also exported around the world.

Ironbridge Gorge Museum

Coach Road, Coalbrookdale, Shropshire
England, TF8 7DQ

Tel 01952 432166
Fax 01952 435999
e-mail info@ironbridge.org.uk
Web http://www.ironbridge.org.uk/

Foundry work and the rolling of wrought iron are demonstrated at the Blists Hill site (check rolling times in advance of a visit). (*Illustration 210*). The wrought iron works contains a steam hammer and rolls from the Atlas Forge in Bolton and is housed in a splendid early nineteenth century workshop from the Admiralty Dockyards at Woolwich. The extensive research library (e-mail: library@ironbridge.org.uk), adjacent to the Coalbrookdale Museum of Iron, holds material relating to the iron industry, bridge building, and the life and work of Thomas Telford, for example. (Illustrations 274 and 276). Highlights of the Museum's collections can be viewed at

http://www.ironbridge.org.uk/d_collections.asp

Auld Kirk Museum

Cowgate, Kirkintilloch, G66 1AB

Tel: 0141 578 0144
Fax: 0141 578 0140

Collection of castings, patterns and archives for Lion Foundry, Southbank and Star Ironworks of Cameron Robertson Ltd.

Illustration 273 The Iron Bridge (copied at half-scale), Blist's Hill, Ironbridge, Coalbrookdale
Uprights cast in 2001 by H Downs & Sons of Huddersfield. The honeycombing is the result of moulding in an open sand bed, in the manner of the originals. This may have been reduced by spreading loose sand over the top of the molten casting. (Picture: T. Swailes)

Illustration 274 Callender House, Falkirk Museums (Picture: T. Swailes)

9.4 Libraries, archives and information services

The Mitchell Library, Glasgow

North Street, Glasgow, G3 7DN

Tel 0141 287 2999
e-mail lil@cls.glasgow.gov.uk
Web http://www.glasgowlibraries.org/

One of the largest public reference libraries in Europe, and home of the Glasgow City Archives.

William Patrick Library

(Information & Archives)
2 West High Street, Kirkintilloch, Glasgow, G66 1AD

Tel: 0141 776 8090
Fax: 0141 776 0408

Kirkintilloch
e-mail libraries@eastdunbarton.gov.uk

Contains Lion Foundry and Southbank Ironworks archives.

The National Archives of Scotland

Historical Search Room
H M General Register House
2 Princes Street, Edinburgh, EH1 3YY

Tel 0131 535 1334
Fax 0131 535 1328
e-mail enquiries@nas.gov.uk

West Search Room, West Register House
Charlotte Square, Edinburgh. EH2 4DJ

Tel 0131 535 1413
Fax 0131 535 1411
e-mail wsr@nas.gov.uk
Web http://www.nas.gov.uk/

The National Archives of Scotland holds historical records relating to canals, railways, mining, shipbuilding and most other industries, private, business, estate and burgh papers, maps and architectural and engineering plans (Illustration 277). Some material is stored off-site and two days notice is required for viewing. Useful fact sheets downloadable from the web as *.pdf files include 'Buildings' and 'Estate Records'.

Illustration 275 An iron truss of 44 feet span, from Goldsmith's Hall, City of London (c.1830) Relocated to Ironbridge Gorge Museum in 1990 The bottom tie bars are wrought iron and the upper members are cast iron. An ornate plaster ceiling was suspended below the truss, on wrought iron rods. The truss bears a close similarity to a design by Thomas Tredgold (Sutherland, 1979). (Picture: T. Swailes)

Relevant material may be held in other archives in Scotland, or elsewhere in Britain, so before visiting the National Archives of Scotland, a search of the on-line National Register of Archives (below) maintained by the Historical Manuscripts Commission is recommended. The National Archives of Scotland are also a supporter of the Scottish Archives Network, or SCAN (http://www.scan.org.uk/)

SCAN makes available on-line the catalogues of 51 Archives in Scotland, from Aberdeen City to West Lothian Council and also makes available, at a cost, digital images of wills at **http://www.scottishdocuments.com/**

The National Library of Scotland

George IV Bridge, Edinburgh, EH1 1EW

Tel 0131 226 4531
Fax 0131 622 4803
e-mail enquiries@nls.uk
Web http://www.nls.uk/

The catalogue to the main collection of printed materials containing over three million records is available on-line, as is the manuscript collection catalogue. On-line resources include Scottish Bibliographies on-line, and CAIRNS, a combined catalogue searcher for academic and other major libraries across Scotland.

National Register of Archives

Web http://www.hmc.gov.uk/nra/search_nra.htm

The indexes to the NRA can be searched by place name, family name, personal name or corporate name.

The ARCHON Directory

Web
http://www.hmc.gov.uk/archon/searches/locresult.asp?lctry=Scotland

ARCHON contains an on-line directory of over 200 Scottish archives.

A2A - Access to Archives

Web http://www.a2a.pro.gov.uk/

An on-line searchable database, including the catalogues of about 200 record offices and other repositories of archives in England. Some material relevant to Scottish buildings and structures is held in England.

The British Library

Web http://www.bl.uk/

The British Library Public Catalogue of over ten million items is searchable on-line, as is the catalogue for the Manuscripts collection. Some printed items may be supplied as loans or photocopies. The web site provides links to other library catalogues around the world.

Construction Industry Resource Centre Archive (CIRCA)

Kimmins Hill, Meadow Lane, Dudbridge
Gloucestershire, GL5 5JP

Tel 0117 968 7850 (evening)
07966 227 575 (daytime)
Fax 0117 962 6614

A repository, in a mill with timber floors and cast iron columns, for construction products literature and the contents of defunct construction-related libraries, for example the Property Services Agency. The collection contains some pieces of buildings, including a variety of cast iron columns and a c.1820 timber beam 'flitched' with internal iron trussing.

International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM)

Via di San Michele 13, Rome, Italy

Tel +39 06 585531
e-mail iccrom@iccrom.org
Web www.iccrom.org

An inter-governmental organisation established in Rome in 1959 with a worldwide mandate to promote the conservation of both movable and immovable

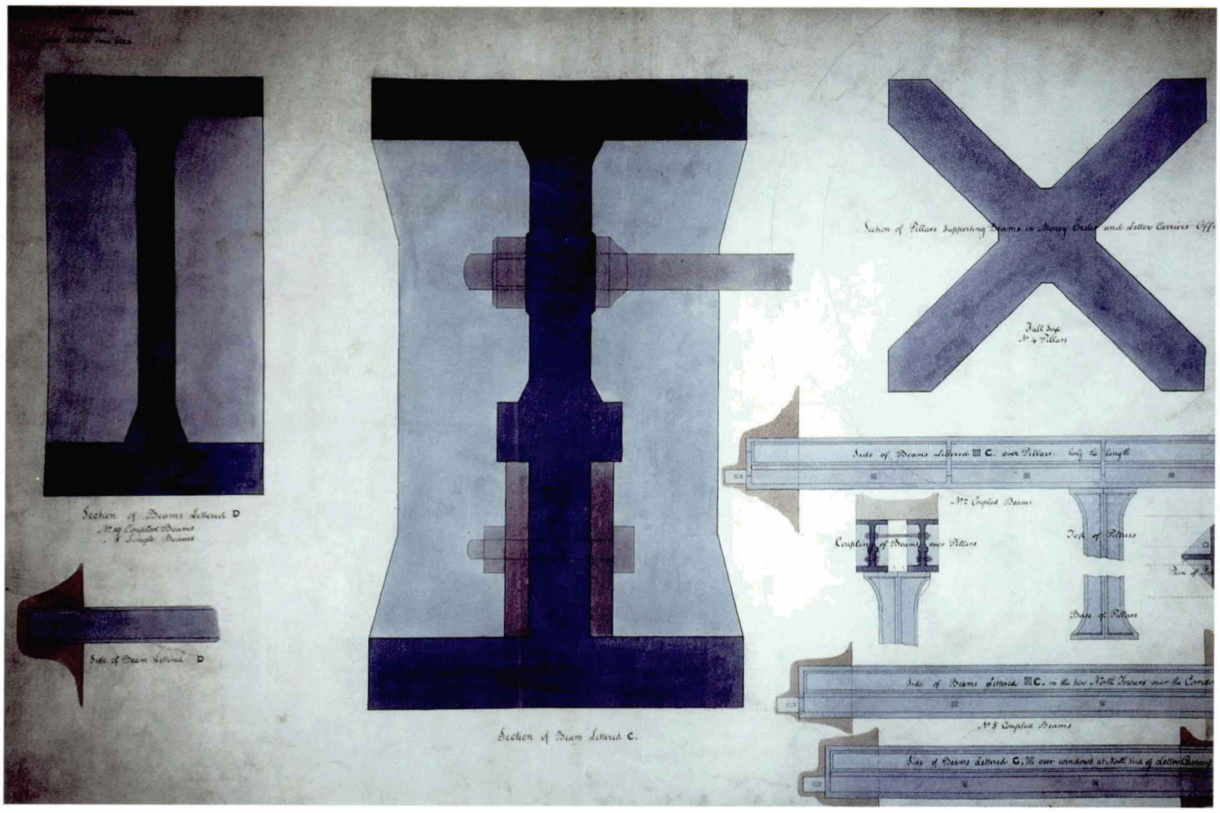


Illustration 276 Edinburgh Post Office (1859) Cast iron beam and column details (Picture: National Archives of Scotland) (See also illustration 177)

heritage in all its forms. The library holds 66,000 volumes and 750 periodicals in the field of international cultural heritage preservation. The library catalogue is searchable on-line and for many foreign language publications, including journal papers, an informative abstract in English may be viewed. The web links database provides access to a comprehensive bank of conservation/restoration related international web sites enabling direct access to external resources and research material.

9.5 Trusts, societies and interest groups

The Architectural Heritage Fund

Clareville House, 26/27 Oxendon Street
London, SW1Y 4EL

Tel	0207 925 0199
Fax	0207 930 0295
e-mail	ahf@ahfund.org.uk
Web	http://www.ahfund.org.uk/

The Architectural Heritage Fund (AHF) helps to repair and regenerate historic buildings by helping voluntary and community groups, with grants, low-interest loans, and advice. The AHF supports charitable organisations and may help to set up a Building Preservation Trust (BPT) where none exists. A leaflet on BPT's can be downloaded from the Web, where information on sources of funding can also be found.

The Architectural Heritage Society of Scotland

The Glasite Meeting House, 33 Barony Street
Edinburgh, EH3 6NX

Tel	0131 557 0019
Fax	0131 557 0049
e-mail	director@ahss.org.uk
Web	http://www.ahss.org.uk/

The AHSS is concerned with the protection, preservation, study and appreciation of Scottish buildings. Visits, tours and talks are organised by regional groups. Local cases panels monitor applications for listed building consent, and for planning permission in conservation areas, and offer advice and guidance regarding the applications to the local planning authorities. Publications are the annual journal Architectural Heritage and the twice yearly Magazine.

The Association for Industrial Archaeology

c/o School of Archaeological Studies
University of Leicester
Leicester, England, LE1 7RH

Tel	0116 252 5337
Fax	0116 252 5005
e-mail	aia@le.ac.uk
Web	http://www.industrial-archaeology.org.uk/

Publications are the journal Industrial Archaeology Review, published twice a year, and IA News, a quarterly magazine. The surviving evidence of industrial activity is a focal point and theme, in the UK and abroad.

The Construction History Society

c/o The Chartered Institute of Building
Englemere, Kings Ride, Ascot, Berkshire
England, SL5 8BJ

Tel 01344 630734
Fax 01344 630777
e-mail pharlow@ciob.org.uk
Web http://www.fp.rdg.ac.uk/wkc1/chs/

The Construction History Society disseminates research and information about historical buildings and construction techniques and organises site visits and lectures. Since 1985 the Society has published Construction History, a journal devoted to the study of all aspects of the history of building and construction history. The Society newsletter and various discussion papers are available on-line.

Edinburgh World Heritage Trust

5 Charlotte Square, Edinburgh, EH2 4DR

Tel 0131 220 7720
Fax 0131 220 7730
e-mail info@ewht.org.uk
Web www.ewht.org.uk

The centre of Edinburgh was designated a World Heritage site by UNESCO in 1995. Established in 1999, the Trust is an amalgamation of the Edinburgh New Town Conservation Committee and the Edinburgh Old Town Renewal Trust and is supported by Historic Scotland and the City of Edinburgh Council. The Trust awards grants for appropriate external repairs, advises central and local government on major policy and development issues and monitors and promotes the World Heritage Site.

The Garden History Society

Christopher Dingwall
The Glasite Meeting House, Edinburgh, EH3 6NX

Tel/Fax 0131 557 5717
e-mail conservation@ghsscotland.freeserve.co.uk
Web http://www.gardenhistorysociety.org/

One of the main aims of the society is to promote the protection and conservation of historic parks, gardens and designed landscapes, and to advise on their restoration. Some members' interests include garden structures.

Glasgow Conservation Trust West

30 Cranworth Street, Glasgow, G12 8AG

Tel/ Fax 0141 339 0092
Web
http://users.colloquium.co.uk/~GLASGOWWEST/home.htm

The GCTW is a registered charity with a remit to conserve and promote the historic West End of Glasgow. In partnership with Glasgow City Council and Historic Scotland, the Trust encourages original research, publishes conservation information and co-ordinates capital grants for restoration projects. The Trust's West End Conservation Manual is a detailed technical guide, with section 4.0 on 'Ironwork'. A Guide for Appropriate Repairs, Alterations, Decoration and Extensions to Buildings, Gardens and Backcourts in the West End is available on-line and includes a short section on 'Ornamental Railings'.

The National Trust For Scotland

Wemyss House, 28 Charlotte Square
Edinburgh, Scotland, EH2 4ET

Tel 0131 243 9300
Fax 0131 243 9301
e-mail
Web
http://www.thenationaltrustforscotland.org.uk/

The National Trust for Scotland protects and promotes Scotland's natural and cultural heritage for the enjoyment of present and future generations. The Trust cares for several of Scotland's 'great' houses, some with hidden structural ironwork, as well as smaller properties.

The Newcomen Society

The Science Museum, London, SW7 2DD

Tel/Fax 0207 371 4445
e-mail thomas@newcomen.com
Web http://www.newcomen.com/

The world's oldest learned society devoted to the history of engineering and technology. Contact details for the Honorary Secretary to the Scottish Branch are given on the web site. Transactions are published twice a year (a consolidated list of contents and an author index is on the web site, under 'Archives') and members receive the Bulletin three times a year. Other occasional publications are also issued. Meetings are held at the Glasgow Museum of Transport, 1 Bunhouse Road.

The Phoenix Trust

19–22 Charlotte Road, London, England, EC2A 3SG

Tel 0207 613 6430
Fax 0207 613 6439
e-mail thephoenixtrust@princes-foundation.org
Web http://www.thephoenixtrust.org.uk/

Associated with The Prince's Foundation, the Phoenix Trust acquires, repairs and finds new uses for major historic buildings which might otherwise fall into decay or face demolition, for the benefit of the communities in which they stand, and the public at large. Some details of major projects in Scotland at Anchor Mills, Paisley and Stanley Mills, Perthshire (see Structures Index), are given on the web.

The Scottish Civic Trust

The Tobacco Merchants House
42 Miller Street, Glasgow, G1 1DT

Tel 0141 221 1466
Fax 0141 248 6952
e-mail
Web

A voluntary organisation working to raise the quality of the built environment. The Trust maintain the 'Buildings at Risk Register', which is funded by Historic Scotland (see 'SAVE' below, for England and Wales). Regularly up-dated publications include 'The Buildings at Risk Bulletin' and 'Sources of financial help for Scotland's historic buildings'. A directory of local civic societies and amenity groups is published on the Trust's web site.

The Scottish Industrial Heritage Society

22, Alexandra Place
Stirling FK8 1ON

web http://www.sihs.co.uk

The Society is concerned to promote the recording and preservation, in situ and in industrial museums, of both unique and representative evidence of Scotland's industrial past. A bulletin and a review are published.

The Society of Architectural Historians of Great Britain

Pixham Mill, Pixham Lane, Dorking
Surrey, England, RH14 1PQ

e-mail website@sahgb.org.uk
Web http://www.sahgb.org.uk/

A table of contents for the journal Architectural History is available on-line, from volume 1 in 1958.

The Society for the Protection of Ancient Buildings in Scotland

The Glasite Meeting House
33 Barony Street, Edinburgh, EH3 6NX

Tel/ Fax 0131 557 1551
e-mail info@spabscotland.freeserve.co.uk
Web www.spab.org.uk/scotland

SPAB is a pressure group, founded by William Morris of the 'arts and crafts' movement, with the aim of saving old buildings from decay, demolition and damage. What Morris would have thought of the conservation of iron structures and buildings of 'the industrial age' is an interesting question. SPAB members sign up to the 1877 Morris manifesto and receive the quarterly bulletin SPAB News. The Society runs courses on the conservation and repair of traditional building materials, including historic ironwork, organises visits, talks and technical events, and publishes technical pamphlets and information sheets.

The Georgian Group

6, Fitzroy Square, London, W1T 5DX

Tel 0207 387 1720
Fax 0207 387 1721
e-mail info@georgiangroup.org.uk
Web http://www.georgiangroup.org.uk/

The Georgian Group campaigns against the neglect, maltreatment and destruction of Georgian buildings, parks and gardens, in England and Wales only, although the work of architects of importance in Scotland, such as the Adam brothers, are of particular interest. A list of publications available for purchase is on-line, as is a listing of the contents of the Georgian Group Journal, from v1 in 1991.

Save Britain's Heritage (SAVE)

70 Cowcross Street, London, EC1M 6EJ

Tel 0207 253 3500
Fax 0207 253 3400
e-mail save@btinternet.com
Web http://www.savebritainsheritage.org/main.htm

A charitable organisation that campaigns publicly for endangered historic buildings. A list of publications is available on-line, including 'Bright future: the reuse of industrial buildings' (1990). SAVE maintains a register of buildings at risk in England and Wales, while for Scotland a register is maintained by The Scottish Civic Trust.

The Victorian Society

1 Priory Gardens, Bedford Park, London, W4 1TT

Tel	0208 994 1019
Fax	0208 747 5899
e-mail	admin@victorian-society.org.uk
Web	http://www.victoriansociety.org.uk/

The Victorian Society is concerned with the study and protection of Victorian and Edwardian architecture and other arts, in England and Wales only. A list of publications is available on-line, including a series of booklets 'Care for Victorian Houses', one of which is 'A brief guide to decorative ironwork in Victorian and Edwardian houses' (1994).

9.6 Professional institutions and accreditation bodies

See also The Institution of Civil Engineers and the Institution of Structural Engineers for the 'CARE' scheme

The AABC Register (Register of Architects Accredited in Building Conservation)

33 Macclesfield Road, Wilmslow, Cheshire, SK9 2AF

Tel	01625 523784
Fax	01625 548328
e-mail	info@aabc-register.co.uk
Web	www.aabc-register.co.uk

Historic Scotland is represented on the Board of ACCON, a limited company trading as the AABC Register (set up after the failure of the RIBA in 1999 to set up a register). Registration of an individual architect involves assessment of knowledge and experience in the field by two qualified architectural assessors and one non-architect who is informed and interested in building conservation.

COTAC (Conference on Training in Architectural Conservation)

The Building Crafts College
Kennard Road, Stratford, London, E15 1AH

Tel	0208 221 1150
Fax	0208 221 2708
e-mail	cotac@tcp.co.uk
Web	http://www.cotac.org.uk/

A registered charity concerned with training and education for the protection and preservation of historic buildings and structures. Members of the Conference are institutions with an interest in conservation (there are no individual members). COTAC sets standards for conservation qualifications from craft to professional levels. The website includes listings of degree level and other courses in conservation and an index of conservation-related articles.

The Institute of Historic Building Conservation (IHBC)

Jubilee House, High Street, Tisbury, Wiltshire
England, SP3 6HA

Tel	01747 873133
Fax	01747 871718
e-mail	admin@ihbc.org.uk
	scotland@ihbc.org.uk (Scotland)
Web	http://www.ihbc.org.uk/

Formerly the Association of Conservation Officers (ACO), IHBC is the professional institute representing conservation professionals in the public and private sectors in the United Kingdom and Ireland. Details of degree courses in Building Conservation recognised by the IHBC are given on the web site. It has approximately 1360 members, divided between 15 branches. Members receive a quarterly magazine 'Context'. Some short 'guidance notes' are published freely on the web.

The Institution of Civil Engineers

One Great George Street, Westminster
London, SW1P 3AA

Tel	0207 222 7722
Fax	0207 222 7500
Web	http://www.ice.org.uk/

The Library catalogue (100,000 titles) and Publications catalogue are searchable on-line. Full text ICE Proceedings (from 1836 onwards) and Conference papers may be purchased and downloaded.

Extensive archives (view by prior appointment). A pamphlet: "Save Engineering Records" is available, giving advice on the preservation of both past and present engineering archives. The Institution's Panel for Historical Engineering Works (PHEW) promotes awareness of our engineering heritage, identifies civil engineering works worthy of recording and/or preserving for posterity and maintains an index of civil engineering works which have been recorded or listed or preserved. PHEW quarterly newsletters from March 1998 are on-line and the Historical Engineering Works Index includes several Scottish iron bridges.

ICE and IStructE have established CARE, a register of engineers accredited in conservation. Coincident with the establishment of CARE, an e-mail discussion group, CEHX (the Civil Engineering heritage exchange), was been launched as a forum for those interested in historical and conservation issues in civil and structural engineering, and construction generally. For details, contact: mike.chrimes@ice.org.uk

Local Associations of the ICE in Scotland

The Glasgow and West of Scotland Association
http://www.ice-westscotland.org.uk/

The East of Scotland Association
http://www.ice-eastscotland.org.uk/
(with Edinburgh, Dundee and Aberdeen branches)

There is a small museum display of civil engineering material at Heriot-Watt University.

The Institution of Engineers and Shipbuilders in Scotland

Clydeport, 16 Robertson Street, Glasgow, G2 8DS

Tel	0141 248 3721
Fax	0141 221 2698
e-mail	Secretary@iesis.org
Web	http://www.iesis.org/

The IESIS, founded in 1857, provides a forum for individual members from engineering and related disciplines to discuss and exchange information, generate ideas, and promote a wider understanding of the role of the engineering profession in society. A programme of meetings and events is published on the web. Members have free access to the academic libraries of Glasgow and Strathclyde Universities, to which the library of the IESIS was donated. Transactions are published annually. A database of papers from 1857 onwards is available to members (though not on-line).

The Institution of Structural Engineers

11 Upper Belgrave Street, London, SW1X 8BH

Tel	0207 235 4535
Fax	0207 235 4294
e-mail	mail@istructe.org.uk
Web	http://www.istructe.org.uk/

The international professional body for Structural Engineers, with around 22,000 members, combining the roles of a learned society with that of a qualifying body setting and maintaining standards for professional engineers. The Institution runs a number of Continuing Professional Development (CPD) courses on aspects of appraisal, conservation and refurbishment of existing structures. The journal The Structural Engineer is published twice a month, and past papers can be located via the on-line library database. Library loans to members are free of charge.

The IStructE Informed Study Group on the History of Structural Engineering, established in 1972, meets regularly between May and October, details of meetings being notified to members via e-mail. Group membership is mixed, including architects, historians and surveyors and other enthusiasts, as well as engineers. Structural iron has been a topic of discussion at many meetings and is the semi-obsessive interest of several group members. Short visits to historic sites and works are arranged as well as longer study tours in Britain and abroad.

The Scottish Branch has over 1600 members. Details of meetings are published on the Branch web site:

Web
http://www.istructe.org.uk/branch/Scottish/frameset.asp?BID=6&Name=Scottish

ICE and IStructE have established CARE, a register of engineers accredited in conservation. Coincident with the establishment of CARE, an e-mail discussion group has been launched as a forum for those interested in historical and conservation issues in civil and structural engineering, and construction generally. For details, contact: mike.chrimes@ice.org.uk

The International Council of Monuments and Sites (ICOMOS)

70 Cowcross Street, London, EC1M 6EJ

Tel	020 7566 0031
Fax	020 7566 0045
e-mail	admin@icomos-uk.org
Web	www.icomos.org/uk/

Created by UNESCO in 1965, ICOMOS is the international authority on monument conservation, independent of governments. ICOMOS advises UNESCO on World Heritage Sites, and promotes international best practice in the conservation and management of cultural heritage through publications, research, conferences and seminars. Details of individual membership of ICOMOS are available on-line. Contact the author of this Practioners' Guide for details of ICOMOS committee work relating to iron structures.

Royal Incorporation of Architects in Scotland (RIAS)

15 Rutland Square, Edinburgh, EH1 2BE

Tel	0131 229 7545
Fax	0131 228 2188
Web	http://www.rias.org.uk/

The RIAS is the professional institute for chartered architects in Scotland. For short descriptions of each of the excellent RIAS architectural guides to the cities and regions of Scotland, published by the Rutland Press, go to http://www.rias.org.uk/illustrated_architectural_guides.htm

The Royal Institute of British Architects (RIBA)

66 Portland Place, London, W1B 1AD

Tel 0207 580 5533
Fax 0207 255 1541
e-mail info@inst.riba.org
Web http://www.architecture.com/

The RIBA hosts architecture.com, a very extensive web portal for the built environment. The RIBA British Architectural Library is one of the best collections of architectural material in the World. The catalogue includes books, photographs, drawings, manuscripts and a biographical database of architects and is at

http://store.yahoo.com/riba-library/oncat.html

The Royal Institution of Chartered Surveyors (RICS)

RICS Contact Centre, Surveyor Court, Westwood Way, Coventry CV4 8JE

Tel 0870 333 1600
e-mail contactrics@rics.org
Web http://www.rics.org/building_conservation/

The RICS Building Conservation Forum runs an accreditation scheme for surveyors in conservation. The forum publishes a regular series of short guides on issues on matters related to historic buildings, and runs a programme of events for members. Advice on-line includes guidance on 'surveying safely', covering risk assessments with respect to premises, personal safety and the safety of the public, and the legal obligations of the surveyor.

The Institute of Conservation (ICON)

3rd Floor, Downstream Building, 1 London Bridge London SE1 9BG

Tel 020 7785 3805
Fax 020 7785 3806
Web <http://www.instituteofconservation.org.uk>

Icon brings together over three thousand individuals and organisations. Its membership embraces the wider conservation community, incorporating not only professional conservators in all disciplines, but all others who share a commitment to improving understanding of, and access to, our cultural heritage. The Institute aims to advance knowledge and education in conservation and achieve the long term preservation and conservation of cultural heritage. ICON also maintains the Conservation Register. The Conservation Register provides detailed information on conservation-restoration businesses based in the UK and Ireland including contact details, referenced examples of previous work and the qualifications of members of staff. It is searchable by specialist skill and geographical location and each business has been required to meet rigorous criteria which include professional accreditation; the information is regularly updated. To use the Conservation Register, please visit www.conservationregister.com <http://www.conservationregister.com/>

9.7 Specialist contractors, service providers and research organisations

Heritage Engineering (The Industrial Heritage Company Ltd)

(Incorporates Walter MacFarlane and Company Limited, and Saracen Castings)

22-24 Carmyle Avenue, Glasgow, G32 8HJ

Tel 0141 763 0007
Fax 0141 763 0583
e-mail sales@heritageengineering.com
Web http://www.heritageengineering.com/

A firm that specialises in the restoration of cast and wrought iron and has restored many Scottish iron-framed structures, from drinking fountains to conservatories and Winter Gardens. As well as providing contract services, advice and guidance is given on a consultancy basis.

Scottish Foundries

Web http://www.scottishfoundries.co.uk/

The web site claims to give comprehensive and up to date details of every Scottish Foundry (in May 2005, there were 24). There is a link to a sister web site for the whole of the United Kingdom. The Scottish companies listed below collectively have experience of cast iron in its various architectural and structural forms.

Ballantine Bo'ness Iron Co. Ltd

Links Road, Bo'ness, EH51 9PW

Tel 01506 822 721
Fax 01506 827326
e-mail info@creativeironworks.co.uk

Ironfounders and engineers providing new ironwork and refurbishment to existing ironwork. Over 250,000 patterns are held, including fencing, monuments, post boxes, lamp posts, manhole covers and extensive ornamental structures.

Charles Laing & Sons Ltd

28 Beaverbank Place, Edinburgh, EH7 4ET

Tel	0131 556 3160
Fax	0131 556 2484
e-mail	admin@laingsfoundry.co.uk
Web	www.laingsfoundry.co.uk

A traditional small green sand foundry, able to supply new decorative ironwork and restore original examples of architectural ironwork.

George Taylor & Co. (Hamilton) Ltd

Kemp Street, Hamilton, ML3 6PQ

Tel	01698 284949
Fax	01698 891285
e-mail	office@gtham.co.uk
Web	www.gtham.co.uk

A foundry specialising in the production of spheroidal graphite (ductile) and grey (flake graphite) iron castings up to 3 tonnes that has supplied ductile iron castings for use in bridge works.

Carnoustie Castings Ltd

2a Anderson Street, Carnoustie, DD7 7LZ

Tel	01241 859920
Fax	01241 856233

A jobbing foundry. Architectural ironwork castings have included balustrades, balconies, window frames and rainwater goods.

Archibald Young Ltd

Founders and Engineers, Milton Road
Kirkintilloch, G66 1SY

Tel	0141 776 7701
Fax	0141 775 1743
e-mail	ianyoung@archibaldyoung.co.uk
Web	www.archibaldyoung.co.uk

Specialist in copper-based aluminium and iron alloys from 0.1kg to 1 tonne in weight.

British Coatings Federation Ltd

James House, Bridge Street, Leatherhead
Surrey, England, KT22 7EP

Tel	01372 360 660
Fax	01372 376 069
e-mail	mail@coatings.org.uk
Web	http://www.coatings.org.uk

The Building Research Establishment (BRE)

Garston, Watford, England, WD25 9XX

Tel	01923 664 000
e-mail	enquiries@bre.co.uk
Web	http://www.bre.co.uk/

BRE Scotland
Kelvin Rd, East Kilbride, Glasgow, G75 0RZ

Tel	01355 576200
Fax	01355 576210
e-mail	eastkilbride@bre.co.uk

A leading centre of expertise on buildings and materials (particularly concrete, masonry and timber), construction, energy, environment, fire and risk, and a provider of research-based consultancy, materials testing and certification services.

Castings Technology International

7 East Bank Road, Sheffield, England, S2 3PT

Tel	0114 272 8647
Fax	0114 273 0852
Web	http://www.castingsdev.com/

CTI is a membership-based limited company that carries out research and development relevant to the manufacture and use of metal castings and provides technical services to its members. It was formed in a merger that involved the British Cast Iron Research Association (BCIRA). Services include non-destructive testing, chemical analysis, metallographic examination and mechanical testing.

The Construction Industry Research and Information Association (CIRIA)

6 Storey's Gate, London, SW1P 3AU

Tel	0207 222 8891
Fax	0207 222 1708
e-mail	enquiries@ciria.org.uk
Web	www.ciria.org.uk

CIRIA is a research association with 500 corporate members that carries out collaborative research and publishes technical reports. Interim reports of current CIRIA research projects can be found on the web site.

Dorothea Restorations Ltd

New Road, Whaley Bridge, High Peak, Derbyshire
England, SK23 7JG

Tel	01663 733544
Fax	01663 734521
e-mail	north@dorothearestorations.com
Web	http://www.dorothearest.co.uk/

A long-established firm specialising in restoration, conservation and preservation in the fields of engineering and architectural metalwork. As well as providing contract services, advice and guidance is given on a consultancy basis.

The Paint Research Association

8 Waldegrave Road, Teddington, Middlesex
England, TW11 8LD

Tel	0181 977 4427
Fax	0181 943 4705
e-mail	coatings@pra.org.uk
Web	http://www.pra.org.uk

The Real Wrought Iron Company

Carlton Husthwaite, Thirsk, North Yorkshire, England

Tel	01845 501415
Fax	01845 501072
e-mail	enquiry@realwroughtiron.com
Web	http://www.realwroughtiron.com/

Suppliers of genuine wrought iron to blacksmiths, and for use in the restoration of historic ironwork. The material is available in square, round or flat bar form or in plates of up to 1/2 inches thick. More complex shapes such as glazing bars may be rolled if economical for the quantity required, or forged.

Advice on-line is given via the Wrought Iron Advisory Centre,

http://www.realwroughtiron.com/wiac.htm

A sister company with the same contact details, Chris Topp & Co., gives advice and guidance on all aspects of iron and forgework, including wrought iron, cast iron and steel

http://www.christopp.co.uk/index.html

The Steel Construction Institute

Silwood Park, Ascot, Berkshire, England, SL5 7QN

Tel	01344 623345
Fax	01344 622 944
e-mail	reception@steel-sci.com
Web	http://www.steel-sci.org/

SCI is an independent member-based organisation that operates a technical advice service, principally concerned with modern steel structures, free to corporate members. Some publications (such as P138: Appraisal of Existing Iron and Steel Structures, on which SCI runs a one day CPD course) are available to members on-line via Steelbiz.

The Traditional Paint Forum

c/o The National Trust for Scotland
28 Charlotte Square, Edinburgh, EH2 4ET

Tel	0131 243 9449
Fax	0131 243 9599
e-mail	dmcdonald@nts.org.uk

The Traditional Paint Forum was founded to promote a better understanding and appreciation of traditional paint. It promotes its aims by exchanging, collating and disseminating information through the publication of a regular newsletter, journal, and by holding meetings and conferences.

The Transport Research Laboratory (TRL)

Old Wokingham Road, Crowthorne, Berkshire
England, RG45 6AU

Tel	01344 770007
Fax	01344 770880
e-mail	enquiries@trl.co.uk
Edinburgh office e-mail	scotland@trl.co.uk
Web	http://www.trl.co.uk/1024/mainpage.asp

TRL is the leading UK centre for transport research, with around 500 staff, with work that includes an involvement in the development of design and assessment rules for bridge structures. The catalogue of all TRL publications is downloadable from the web as a *.pdf file and there is a searchable on-line catalogue of reports from 1966 onwards.

TWI (The Welding Institute)

Granta Park, Great Abington, Cambridge
England, CB1 6AL

Tel	01223 891162
Fax	01223 892588
e-mail	twi@twi.co.uk
Web	http://www.twi.co.uk/j32k/index.xtp

TWI is an independent research and technology organisation and describes its website as the world's most extensive on-line source of information and advice on welding and joining of engineering materials, including cast iron, wrought iron and steel. Training and certification of operatives and companies is also undertaken.

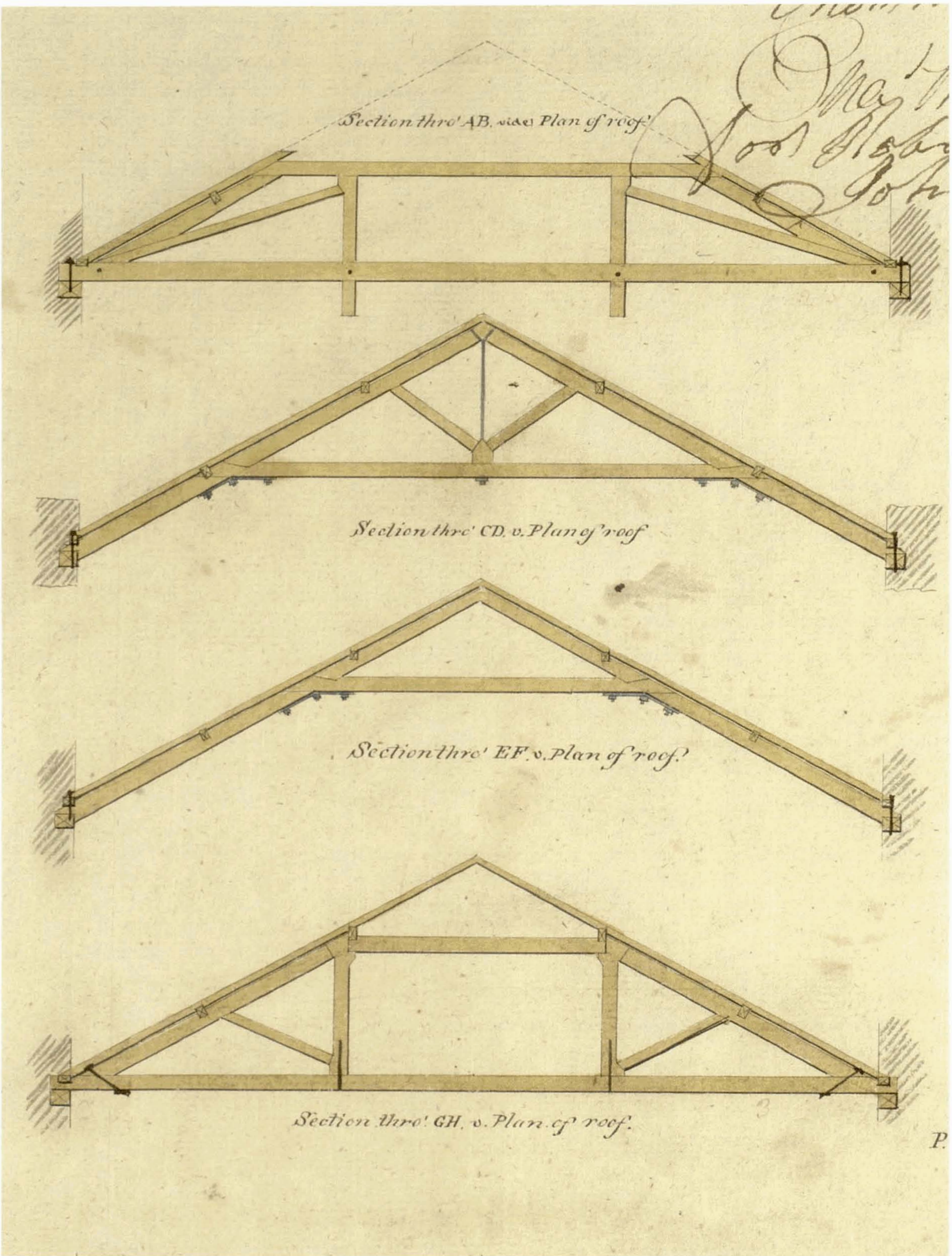


Illustration 277 Part of a drawing for the University of Glasgow prepared in 1806 by Peter Nicholson (Picture: The Drawn Evidence. The University of Glasgow Archive Services))

9.8 Other internet information resources

aecportico
Web http://www.aecportico.co.uk/

A non-profit portal site providing information of relevance to the UK construction industry free of charge. aecportico is owned and run by NBS, a part of RIBA Enterprises Ltd, and wholly owned by the Royal Institute of British Architects.

The Building Conservation Directory
Web http://www.buildingconservation.com/

The on-line version of the Directory includes products and services for over a thousand companies and other organisations. Useful short illustrated articles in the Directory and its sister publications (available on-line in May 2005) included the following:

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Construction Plus
Web:http://www.constructionplus.co.uk/
A subscription portal site based partly on the information assets of publisher Emap's magazines The Architects Journal, Construction News and New Civil Engineer.

The Drawn Evidence
Web:http://www.drawn-evidence.dundee.ac.uk/
A searchable virtual archive of Scottish architectural plans, drawings and related material developed by the University of Dundee, with 10,000 high-resolution digitised images and supporting text (Illustration 278).

Edinburgh Engineering Virtual Library (EEVL)
Web;http://www.eevl.ac.uk/
A focal point for free on-line access to information on engineering, mathematics and computing, principally for students and academic researchers. Under the Engineering Portal Project, EEVL - Engineering will evolve into a portal from which multiple databases can be searched.

Gazetteer for Scotland
Web:http://www.geo.ed.ac.uk/scotgaz/
A geographical database, searchable by 'maps and places' or by 'history time line', the Gazetteer is claimed to be the largest Scottish resource on the web.

The US National Parks Service
Web:http://www.cr.nps.gov/buildings.htm
Several full-text and colour-illustrated guides available on-line are at least to some extent concerned with structural iron. The guides contain a great deal of valuable information, although with historic buildings in America.

Jandl, H.W. (1982), 'Rehabilitating historic storefronts', Preservation Brief 11 Web:http://www2.cr.nps.gov/tps/briefs/brief11.htm

Park, S.C. (1988), 'The use of substitute materials on historic building exteriors', Preservation Brief 16 Web:http://www2.cr.nps.gov/tps/briefs/brief16.htm

Waite, J.G. (1991), 'The maintenance and repair of architectural cast iron', Preservation Brief 27 Web:http://www2.cr.nps.gov/tps/briefs/brief27.htm This Preservation Brief was developed by the New York Landmarks Conservancy's Technical Preservation Services Centre under a co-operative agreement with the National Park Service's Technical Preservation Services, and with partial funding from the New York State Council on the Arts.

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National Parks Service: Illustrated guidelines for rehabilitating historic buildings: The Secretary of the Interior's Standards for Rehabilitation & Illustrated Guidelines for Rehabilitating Historic Buildings - Metals (do's and don'ts for the treatment of historic architectural metalwork) Web:http://www2.cr.nps.gov/tps/tax/rhb/metals01.htm

scottishironwork.org

Web http://www.scottishironwork.org/

The website provides information for those interested in wrought and cast ironwork manufactured or found in Scotland. Resources available include historical information, an online database, technical area and special features.

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11 GLOSSARY

Acid Steel (see also *Basic Steel*)
A relatively cheap, hard *Steel* (as opposed to *Mild Steel*), made in the latter part of the nineteenth century from *Iron* in an Open-hearth Furnace. The furnace lining being an acid, or chemically neutral material, did not remove phosphorous from the Iron.

Air Furnace
A *Reverberatory Furnace* that was used in the *Foundry* for remelting iron.

Alloy
A substance with the general physical properties of a metal, but consisting of two or more metals combined, or metals and non-metallic elements in intimate mixture or solution. See *Steel*, for example.

Angle Iron
Wrought Iron rolled in the form of an L shape. The term *Angle Iron* is still sometimes used when referring to *Steel* sections of the same shape.

Annealing
Softening of Iron or *Steel* by heating, then slow cooling.

Arch (see also *Jack Arch*)
A structure in the form of a bow, working principally in compression. In traditional masonry construction the arch ring is made of separate pieces or voussoirs, each supporting its neighbour, between abutments providing vertical support and resisting lateral arch thrust.

Astragal (see *Glazing Bar*)

Aqueduct
A bridging structure carrying an open artificial water course.

Bar Iron *(see also wrought iron)*
A term used to indicate wrought iron bar of round, square or rectangular section, as opposed to cast iron. Variants of the term were used to indicate material at an intermediate stage in manufacture (e.g. Muck Bar) or of different grades (e.g. Merchant Bar).

Basic Steel
Steel made using a process perfected by Sidney Gilchrist Thomas in 1879 that enabled *Phosphoric iron* to be used in a *Bessemer Converter*, or Open-hearth Furnace. Phosphorous was taken out of the Iron and removed in the *Slag* through chemical reaction with a basic or alkali furnace lining (e.g. dolomite, a form of Limestone).

Beam
A term for a horizontal spanning or bridging element, less commonly used in the nineteenth century than now. To some extent the word *Beam* is interchangeable with *Joist* (smaller sized beams, for example in buildings) and *Girder* (larger sized beams, for example in bridges).

Belgian Iron
Relatively cheap rolled *Wrought Iron* sections imported in the second half of the nineteenth century, initially in larger sizes than available in Britain. Popularly believed to be of inferior quality to domestic products.

Bending (or Flexure)
The action by which a beam is curved, placing its concave face in compression and its convex face in tension.

Bessemer Converter
A vessel in which air was blown through molten *Pig Iron* or *Cast Iron* to make *Steel* by removing most of the *Carbon.*

Best Iron, Best Best (BB) Iron
Different qualities of Wrought Iron (see also *Lowmoor, Swedish, Treble Best, Yorkshire*).

Blackband Ore
An iron ore containing coal used as fuel in a hot-blast furnace.

Blacking/ Blackening (see *Moulding*)
A *Coke* dust or Plumbago-based coating applied to a mould to prevent fusion of the molten Iron with the sand.

Blast-furnace
A furnace in which iron is extracted from iron ore. The chamber at the centre of the furnace is a cylinder narrowing towards its top, above a funnel-shaped base. Into the open top are fed charcoal or coke as fuel, iron ore, and limestone as a flux. Operation is continuous, an intense heat being maintained by a blast of air at the base, where the furnace is periodically tapped to draw off molten iron.

Bloom
The product of the *Bloomery*. The term was later used to describe the solid mass produced by *Shingling* the balls of *Wrought Iron* taken from the *Puddling Furnace*.

Bloomery
An early form of furnace used for obtaining *Wrought Iron* from *Iron Ore*.

Boiler–plate girder
A girder with a web of one or more wrought iron plates, of the kind from which steam engine boilers were made, to which angle iron flanges are riveted. Large section riveted girders from the late nineteenth century may be steel, or combine steel and wrought iron elements.

Brazing
The joining of two metal parts by heat and using a flux, without the introduction of a more fusible alloy as a solder, and without mechanical working or forging. Sometimes the term brazing is used to describe joints in which hard solder is used. Small parts not loaded structurally might in the past be brazed or 'burned on' to a casting.

Bressummer, or Breastsummer
A large timber beam or lintel with a broad supporting surface, carrying masonry above a shop front or over a bay window, for example.

Bridge
A spanning structure, with a deck or platform, typically enabling passage over water, road or railway. Iron bridges are sometimes hybrids of two or more different forms (For example, *Arch*, *Cable-stayed*, *Girder*, *Suspension*, *Truss* and *Tubular*).

British Standard Beam
A beam section with tapered flanges of a standard size as specified in the list of British Standard Rolled Sections issued by the Engineering Standards Committee in 1903, and in subsequent revised lists. Makers such as Dorman, Long & Co. were rolling several such sections some years before publication of the first British Standard, so BSB sections may not be dateable with certainty.

Brittleness
The property of easily breaking, without significant distortion. See *Ductility*, and *Malleable*, the 'opposite' of brittleness.

Built-up Beam/ Column
Plates and *Rolled Iron* sections riveted (later bolted or welded) together to form a compound section.

Bulb flat
A relatively easily made rolled wrought iron flat with one edge swelled out in the form of a bulb. Together with a riveted flange angle, such sections were useful as deck beams, before rolled I-section joists became widely available.

Cable-stayed Bridge
A *Bridge* with the deck is supported between piers by a series of straight tension cables anchored (or stayed) at height to the piers or masts. Stiffer than a suspension bridge, but with the deck subject to compression to counter the cable tensions.

Camber
An upward curvature built in to a horizontal spanning member to offset deflection under self-weight.

Carbon
A non-metallic element occuring in several forms and a constituent of all organic compounds. Graphite is crystalline and opaque carbon (also called Plumbago), while Charcoal and Coke are amorphous and opaque forms of carbon made by burning off the volatile constituents from wood and coal respectively.

Cast Iron
An alloy of *Iron* and *Carbon* poured molten into moulds. *Grey Cast Iron* (of the *Flake Graphite* form) was used for structural and purposes. (See also *Ductile Iron*, *Malleable Cast Iron*, *Toughened Cast Iron*, *White Cast Iron*).

Cementite
A hard material formed by the chemical combination at high temperature of *Iron* and *Carbon*. Also called iron carbide.

Chafery
A furnace for raising *Wrought Iron* from the *Finery* to forging temperature.

Chaplet
A wrought iron rest for a Core using in *Moulding*, usually comprising a saddle and fixing spike.

Charcoal
A substance with a high carbon content obtained by driving off the volatile constituents of wood by slow heating in a kiln, in the absence of air. Superseded by *coke* as the fuel for the *blast-furnace* by the beginning of the nineteenth century.

Charcoal Iron
A term generally used (like *Swedish Iron*) to denote highest quality wrought iron, made from pig iron from a charcoal fired blast furnace, such as at Bonawe. Reserved for high quality forging and delicate blacksmith's work.

Chilled cast iron
Grey cast iron rendered white, or hard (and brittle) by rapid cooling. Bearing surfaces for moving parts were sometimes 'chilled'.

Cinder Pig
Pig Iron made by mixing *Slag* (or cinder) in with *Iron Ore* in the *Blast Furnace*. The *Hot-blast* made possible the use of waste products in this way, sometimes leading to an inferior end product.

Coke
A substance with a high carbon content obtained by driving off the volatile constituents of coal by heating in covered heaps or kilns, in the absence of air. Stronger than *charcoal*, coke as the fuel made a much taller *blast-furnace* possible.

Cold-Blast Pig Iron (see also *Hot-Blast Pig Iron*)
Iron from a *Blast Furnace* in which the air blast was not heated.

Cold-short Iron (cf. Hot-short)
Wrought iron which crumbles when struck with a hammer when cold.

Column
A vertical support within a building (alternatively *pillar*, or stanchion in heavy construction) or to a bridge (alternatively *pier*), that may form part of a skeletal frame together with *beams* or *girders* or *trusses.*

Compression
An action tending to make a body shorter (the 'opposite' of *Tension*), or causing it to occupy a smaller space.

Core
An internal mould of baked clayey sand used to form a cavity within a casting. For columns the core would have a bar as internal support with hemp rope to support the sand.

Corrugated iron
Rolled wrought iron sheet with ridges and furrows providing stiffness in the direction of span, used for cladding and roof coverings particularly the 1840s, when it might also be galvanised, and as permanent formwork for concrete in fireproof building floors and bridge decks. The term is still applied today to corrugated steel sheet.

Crystalline
The solid form (being made up of crystals), taken by most chemical compounds formed by slow cooling from a molten state. Larger or coarser crystals are associated with slower cooling.

Cupola
A coke-fired foundry furnace for re-melting cast iron.

Deck Beam
A rolled wrought iron or steel beam, of which there were a variety of forms, used in shipbuilding. Wrought iron deck beams were used as roof truss ribs, prior rolled I-sections becoming common.

Direct casting
Casting direct from the blast furnace rather than from re-melted pig iron.

Ductile Iron
A ductile, less brittle form of *Grey Cast Iron*, not developed until 1946, with free graphite present in the form of spheres rather than flakes (also called *Spheroidal Graphite Cast Iron, SG Iron* or *Nodular Iron*).

Eccentric load
A load not passing through the centroidal axis of a structural section, causing bending in a column, torsion in a beam.

Elasticity
The property of recovery of original form after removal of an applied compressive or tensile force. By Hooke's Law, *Stress* is proportional to *Strain.* Young's Modulus of Elasticity is the ratio 'Stress/ Strain'.

Eye-bar
A wrought iron or steel tie bar with an eye at one or both ends for a pinned connection. Eyes were made by forging from the bar but were also made separately and welded on, leading to a local point of weakness. Howard & Ravenhill patent bars were rolled in one piece. Eye-bars in important structures were proof-tested.

Fatigue
Failure of metals by fracture due to the effect of fluctuating stresses acting at a level below the static stress that might cause a ductile failure in wrought iron or steel, or a brittle failure in cast iron. Fatigue is of particular importance in bridge structures.

Ferro-concrete
The late nineteenth/ early twentieth century name for concrete reinforced with bars of iron and later with steel.

Fettling
Cleaning up of castings removed from the mould by breaking off projecting 'gates' and 'fins' with a chisel or hammer, then tidying up with wire brush, grinding wheel etc. Small Blow-holes were routinely plugged with putty, cement or lead.

Filler joist floor
A floor formed of quite closely spaced cast iron, wrought iron or steel joists, filled between with plain concrete.

Finery (see also *Chafery*)
A *Charcoal*-fired hearth used before the invention of *Puddling* for converting *Cast Iron* to *Wrought Iron.*

Fireproof
A term used from the late eighteenth century to describe buildings or building elements made of incombustible materials. The modern equivalent term is fire-resistant.

Fish-bellied Beam (see also *Hog-backed beam*)
A flat-topped beam, increasing in depth towards the centre of its span.

Flake Graphite Cast Iron
Grey Cast Iron in which the free Graphite is present in the form of flakes, or platelets, that act as internal stress raisers and lead to weakness of the material in tension.

Flange (cf. *Web*)
In an iron beam or joist, the horizontal plate(s) at the end(s) of the vertical *Web* plate.

Flexure (see *Bending*)

Flitch beam
A beam in which a plate of cast iron or wrought iron is sandwiched between timbers and held in place by bolts.

Fracture
Rupture or breakage of a solid body by which strength may be impaired. Fractures may be described as brittle, ductile, or fibrous, for example.

Gauge
A term relating to the diameter of wire, the thickness of metal sheet, or the pitch and profile of screw threads.

Gilchrist-Thomas Steel (see *Basic Steel*)

Girder
A large beam. The term is used to describe primary horizontally spanning supports in bridges.

Glazing Bar (or Astragal)
A small section *Rafter* member, or internal framing member in a window, providing direct support to glazing, in a conservatory for example.

Grey (or Gray) Iron (see also *Cast Iron*)
Cast Iron with a relatively high free *Carbon* content, which when fractured cold, shows a granular, greyish surface.

Haematite
Red iron ore, or ferric oxide, Fe_2O_3. A rich ore, containing about 70% of iron.

Hardness
Resistance to indentation, scratching or wear.

Hog-backed Beam (see also *Fish-bellied beam*)
A flat-bottomed beam, increasing in depth, or height, towards the centre of its span. Also called Skewback.

Hoop Iron (see also *Rod Iron*)
Wrought Iron in narrow flexible strips for casks, wagon wheel tyres, etc. A product of the *Slitting Mill*, later produced by grooved rolls.

Hot-blast Pig iron
Iron from a blast-furnace in which the air blast is prior to its entry to the furnace. The hot-blast was the invention of James Beaumont Neilson.

Iron Ores
Compounds of iron with non-metals, chiefly oxygen, occurring naturally in the earth.

Jack (Arch, Rafter)
Jack was a common name in Victorian times for a helping boy, and by extension for anything that gave convenient but apparently slight service. A *Jack Arch* is a secondary element spanning a modest distance between primary beams or girders to form a building floor or bridge deck. The terms *Jack Rafter,* Common Rafter and Secondary Rafter all describe the same roof element.

Joist
In the nineteenth century, a small beam. A modern usage is the distinction between a rolled steel *joist* with tapered flanges and a rolled *universal beam* with near-parallel flanges.

Lowmoor Iron (*see York station*)
A brand of Yorkshire iron, synonymous with superior quality, either cast or wrought.

Malleable (see also *Forge*)
The ability to be formed by hammer blows. Malleability is temperature dependent, pure iron being most malleable at a low white heat.

Malleable Cast Iron
Cast iron rendered less brittle by very slow *Annealing*. Placed in contact with powdered *Haematite* when so treated, the *Carbon* content of small castings was reduced.

Microstructure
The structure of a material as seen under a microscope, or in a photomicrograph. For metals, the surface is polished and acid-etched prior to viewing.

Mild steel
Steel comprising iron with a relatively low carbon content, not affected by heat treatment.

Mine
A name for *Iron Ore*. *Mine Iron* is made from *Ore* only, unlike *Cinder Pig*.

Moulding (see also *Pattern*)
The formation of an impression in a mould in the shape of the casting required. *Green-sand moulding* used the ordinary damp sand of the foundry in iron boxes or *flasks* (the top box being the *Cope* and bottom the *Drag*). Large castings moulded in the foundry floor sand required a top box only. Hollow parts in a casting are formed using *Cores*. *Runners* and *gates* are openings that let the molten iron into the mould and *vents* are openings to let the mould gases out, formed by pricking the sand with a *vent wire* or spike. In *Dry-sand moulding*, used for cores and for some ornamental ironwork, the moulds are dried before use. Painting or coating with a patent or coke dust-based blackening prevented fusing of the sand and molten iron. In *Loam moulding*, the mould was built up without patterns by coating brickwork with *Loam* (typically a clayey sand, with horse dung and cow hair binder and reinforcement), which was then *swept* or trowelled into the desired shape.

Neutral Axis
That part of a curved beam, between its concave and convex face, which is not changed in length by bending.

Nodular Iron
Also known as spheroidal graphite cast iron or ductile cast iron, invented in the first half of the twentieth century. Sometimes used as a replacement for grey cast iron when greater impact resistance is required.

Pattern (see *Moulding*)

Pearlite
Formed on slow cooling of cast iron from the molten state, comprising thin layers of *Cementite* with thicker layers of Iron between.

Phosphoric Iron
Pig Iron or *Cast Iron* with a relatively high Phosphorous content (e.g. *Scotch Iron*).

Pig Iron, or Pig (see also *Cast Iron*)
The product of the blast furnace.

Pile
The arrangement of cut up pieces of *Wrought Iron* for heating, *Shingling*, then rolling.

Pillar (see *Column*)

Principal
A term used to indicate any primary horizontal spanning or bridging member, as opposed to a less important secondary or tertiary member (For example, *Principal* rafter as opposed to Secondary rafter, *Jack* rafter, or Common rafter).

Proof Load
A load above the working load, but below the ultimate load. Proof load testing ensures a factor of safety against failure.

Puddled Bar
Also called Muck Bar, the product of the first rolling in the manufacture of wrought iron.

Puddling (see also *Reverberatory Furnace*)
The process of obtaining wrought iron by burning the carbon and impurities out of cast iron in a *Reverberatory furnace*. In Dry Puddling, introduced by Henry Cort, white cast iron (with low carbon content).

Purlin
A beam member in a roof, spanning beween cross walls, beams or trusses, and supporting secondary rafters.

Rafter
A pitched roof support following the slope of the roof, either as the *Principal* rafter in a truss, or as *Jack*, Common or Secondary rafters supporting the roof covering.

Reverberatory Furnace (see also *Puddling*)
A furnace with separate chambers for the fuel and for the material being heated, the roof of the furnace being shaped to draw air across and reflect heat from one chamber to the other.

Roasting
Slow burning in large heaps, or in a kiln, of broken pieces of *Iron Ore* mixed with coal to drive off water and sulphur. Also called Calcining.

Robustness
The ability of a structure to withstand abnormally severe loads or disturbance without suffering partial collapse or extensive damage.

Rod Iron (see also *Hoop Iron*)
Square section *Wrought Iron*, for conversion to nails and spikes. A product of the *Slitting Mill*, later produced by grooved rolls.

Rolled Iron
Wrought iron formed and shaped by passing heated through rollers.

Rivet
A dowel type fastener of wrought iron or steel, with a shank and head, used for joining two or more pre-holed plate elements. The rivet is heated prior to fitting through the hole and the shank end hammered to close the joint. On cooling and shrinkage of the rivet, the joined pieces are clamped together.

Rust Cement
A jointing or caulking material, based upon iron borings or turnings, for which there were many recipes (for example, from Cassell's c.1907 Engineer's Handbook, 1 lb flour of sulphur, 1 lb sal-ammoniac, 1 cwt. cast iron borings, with sufficient water to mix to a dry paste).

Scarf
An end to end joint between structural members in which the ends are cut on a slope to overlap without an increase in width or depth.

Scotch Iron/ Scotch Pig
Generally relatively cheap hot-blast pig iron (from the 1830s), favoured in mixtures for castings because of its free flowing qualities and very suitable for fine decorative castings.

Shingling
The process of hammering or squeezing the ball from the *Puddling Furnace* to remove slag and impurities and to solidify the metal into a *Bloom*.

Shrink-ring
A wrought iron ring heated and fitted over lugs attached to two or more elements, usually cast iron. On cooling, the ring shrinks and exerts a clamping action on the connected parts.

Siemens-Martin Steel

Skewback (see *Hog-backed*)

Slag
Waste material produced during *Smelting*, or during the making of *Wrought Iron* or *Steel*. Sometimes called Cinder.

Slitting Mill
A water-powered mill for dividing heated Wrought Iron strip into Hoop Iron and Rod Iron by means of rotating cutters on rollers.

Smelting
The process of extracting iron from its ore in a *Blast Furnace*.

Soffit
The underside of a structural member or architectural feature.

Spheroidal Graphite (SG) Iron (see *Ductile Iron*)

Stability
Resistance of a structure to collapse or buckling as a result of a disturbing force; resistance of an element or part of an element to buckling under compression.

Steam Engine
A machine for converting heat into work by utilising the expansion of water on its conversion to steam. Stationary Engines provided an alternative to the water wheel for powering factories, blast furnace bellows and ironworks machinery, and Locomotive Engines revolutionised nineteenth century transport.

Steel
Steel is an *Alloy*, a solid solution of *Carbon* in pure *Iron*.

Strain (see also *Stress*)
In modern engineering terms, *Strain* is the ratio 'change in length/ original length'.

Strength
The ability of a material or structure to resist forces or deformations tending to break it.

Stress (see also *Strain*)
In modern engineering terms, *Stress* is the ratio 'applied force/ original cross-sectional area'. Confusingly, until about 1860, the term *Strain* was generally used instead of stress.

Strut (see *Column*)
A member in compression, with load applied (nominally) along the centroidal axis of the member.

Suspension Bridge
A *Bridge* formed by suspending between piers *Wrought Iron* chains or wire ropes (later *Steel*) and from these a deck. A light and relatively cheap structure, but lacking inherent stiffness.

Suspension Girder (see *Beam/Trussed Girder*)

Swaging (see also *Upsetting*)
The drawing down at the forge, or reducing in size or diameter, of a heated piece of *Wrought Iron*. A *Swage* is a blacksmith's tool for working rounded parts.

Swedish Iron
A term generally used in the eighteenth and early nineteenth century to indicate high quality *Wrought Iron* imported from Sweden.

Tempering
Heat treatment of medium or high carbon *Steel* for tool making. *Steel* heated to cherry red and suddenly cooled or quenched in water or oil is made very hard. Reheating until the surface oxide reaches the desired colour and quenching in water 'lets down' the hardness to the required temper.

Tenacity
A nineteenth century term for tensile *Strength*.

Tension
An action tending to make a body longer (the 'opposite' of *Compression*), or to stretch it.

Tie
A member in *Tension*.

Tied Arch
An arch tied between its feet to eliminate horizontal thrust on supporting abutments.

Toughened Cast Iron (see also *Cast Iron*)
A stronger form of *Cast Iron* first made in the late 1840s by melting with cast iron up to a quarter its weight *of Wrought Iron* scrap, thus reducing the overall carbon content. Probably not much used.

Toughness
Resistance to brittle fracture.

Treble Best Iron (see also *Best, Best Best (BB) Iron*)
Very high quality *Wrought Iron*, superior to *'Best Best'* for a given Brand.

Truss
A skeletal framework in which load is transmitted to supports by compressive and tensile forces in the elements of the framework, rather than by bending. A true truss is fully triangulated.

Trussed Beam/ Girder
A compound element in which a *Beam/ Girder*, generally of timber or *Cast Iron* and working in *Bending*, is strengthened with *Wrought Iron* trussing bars working in *Tension*. Also called a *Suspension Girder.*

Tubular Girder
A rivetted box-section *Wrought Iron Girder* form patented by William Fairbairn in 1846 and widely used in railway *Bridge* construction.

Universal Beam
A steel beam with near-parallel flanges, as first rolled in Britain at Lackenby in the late 1950s. Early parallel flanged sections were rolled in Europe from c.1904 and later in the United States by a rather different process and imported to Britain.

Upsetting (see also *Swaging*)
Increasing the thickness of a piece of heated *Wrought Iron* at the forge by jumping up, or repeatedly striking the end of an upright bar on an anvil.

Web (see also *Flange*)
In an iron beam or joist, the vertical plate with a *Flange* at one or both ends.

Welsh Iron
Relatively expensive *Cold-blast Pig Iron* from Wales bringing qualities of strength and hardness to a mixture for *Cast Iron.*

Wet Puddling (see *Puddling*)

White Cast Iron (see *Cast Iron*)
Cast Iron with a low *Carbon* content, hard and brittle and unsuitable for structural purposes. When fractured cold, shows a granular, greyish surface.

Wire (see also *Gauge*)

Working Load / Working Stress
The maximum load or stress to be sustained by a structural element.

Wrought Iron
A relatively pure form of strong, ductile iron, made by removing the carbon from cast iron in a puddling furnace and shaped by hot rolling or forging

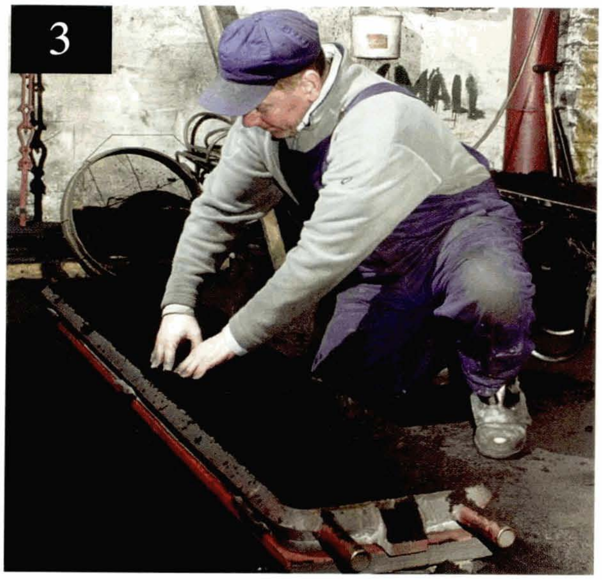
Yorkshire Iron
Iron of high quality, either cast or wrought. Ordinary Yorkshire *Wrought Iron* was generally considered equivalent to *'Best Best'* Staffordshire Iron for example.

APPENDIX A

GREEN SAND MOULDING AND CASTING OF REPLACEMENT STAIR BALUSTERS, CHARLES LAING & SONS LTD, BEAVERBANK FOUNDRY, EDINBURGH

Pattern laid on a wooden board and bottom box placed over. Sand sieved over patterns.

Coarse unsieved sand placed next

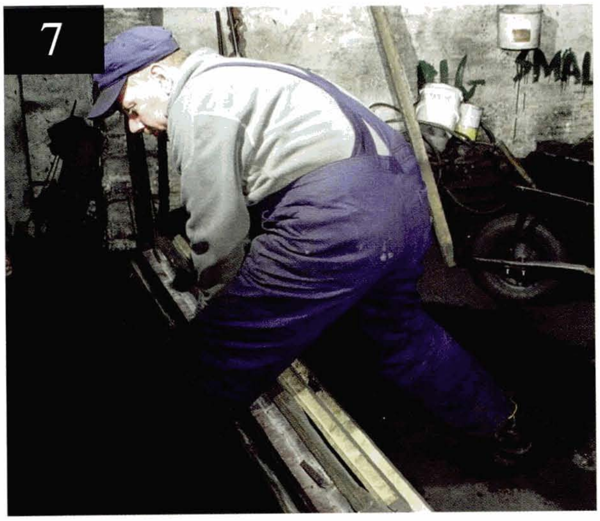


Sand firmed in by hand (or 'fingered')

Ramming within the "Peg Rammer", a plain bar, is followed by ramming with the "Dog Rammer" (as shown)

A board is placed on top, prior to turning over

Clamps are fixed, prior to turning over



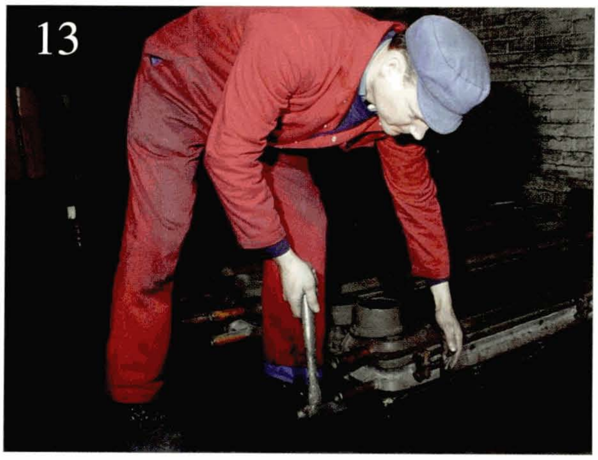
Turning over

The clamps and then the board are removed

Tidying up this surface and edge with a trowel

Patterns removed, sand dusted with parting powder and loose powder blown off with bellows. In the background, a mould with the top box in place, and others weighted down.

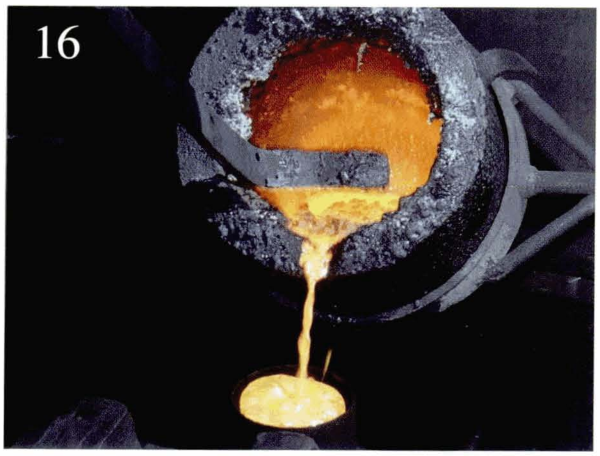
Placing the top box. Note the sand is level across the top box, and all the detail of the pattern is in the bottom box.



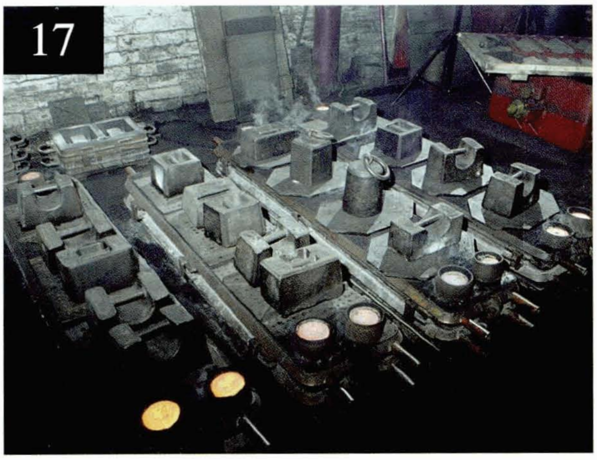
Fixing mould clamps. Note the "pouring bushes" or "slag traps" are now in place.

Mould box detail. Note the vent wire, used for perforating at the sand to aid release of mould slag.

Filling the crucible from the furnace.
"Slagit" (crushed sea shells) is sprinkled on top of the iron in the ladle to help fuse together the impurities which rise to the top.



Filling the mould from the crucible.



Casting complete.

Removing the top box about an hour later.

Removing the balusters from the sand, ready for "fettling"

Any defective castings are recycled. Other raw materials inlcude bus engine block castings and bottle moulds.

(All pictures in Appendix A: Historic Scotland)

APPENDIX B
UNITS AND CONVERSION FACTORS

BRITISH IMPERIAL		METRIC		RECIPROCAL
[1] **LENGTH**		1000mm = 100cm = 1m, 1000m = 1 km		
Fractions of an inch, $^{1}/_{8}$", etc.				
1 inch, may be written 1"	in	**25.40000 millimetres**	mm	0.03937
1 foot, may be written 1' (12 inches)	ft	30.48 centimetres	cm	0.03281
1 yard (3 feet)	yd	0.9144 metres	m	1.0936
1 mile (1760 yards)		1.6093 kilometres	km	0.6214
AREA		1×10^6 mm^2 = 10 000 cm^2 = $1m^2$, 10 000m^2 = 1 hectare		
1 square inch	in^2	645.16 square millimetres	mm^2	1.550×10^{-3}
1 square foot (144 square inches)	ft^2	0.09290 square metres	m^2	10.764
1 square yard (9 square feet)	yd^2	0.8361 square metres	m^2	1.1960
1 acre (4840 square yards)		0.4047 hectares		2.471
1 square mile (640 acres)		259.00 hectares		3.861×10^{-3}
VOLUME		1000 litres = $1m^3$		
1 cubic foot	ft^3	0.0283 cubic metres	m^3	35.34
1 cubic yard (27 cubic feet)	yd^3	0.765 cubic metres	m^3	1.307
1 Imperial pint	pt	0.568 litres	l	1.761
1 Imperial gallon (8 pints)	gal.	**4.54596 litres**	l	0.2200
WEIGHT, MASS		1000g = 1kg, 1000kg = 1 tonne		
1 ounce	oz	28.350 grammes	g	0.03527
1 pound (16 ounces)	lb	**0.45359237 kilogrammes**	kg	2.205
1 stone (14 pounds)				
1 quarter (i.e. a $^{1}/_{4}$ hundredweight)	qtr			
1 hundredweight (112 pounds)	cwt	50.80 kilogrammes		0.0197
1 Imperial ton (20 hundredweight)	ton	1.0160 'metric' tonnes	t^e.	0.984
WEIGHT, MASS, PER UNIT LENGTH				
1 pound per foot run	lb/ft	1.4882 kilogrammes per metre	kg/m	0.6720
DENSITY 1 pound per cubic foot	lb/ft^3	16.02 kg/ m3	kg/m^3	0.06243
[2] **FORCE**		1 kilogramme × 9.81 m/s^2 = 1 newton	N	
		1000 newtons = 1 kilonewton	kN	
STRESS, PRESSURE, LOAD INTENSITY		1 pascal (Pa) = 1 N/m^2	Pa	
1 ton per square inch	ton/in^2	(1.5749 kg/mm^2 × 9.81) = 15.45	N/mm^2	0.06473
1 pound per square inch (p.s.i.)	lb/in^2	(0.07031 kg/cm^2 × 9.81 × 10) = 6.895	kPa	0.145
1 pound per square foot	lb/ft^2	(4.882 kg/m^2 × 9.81) = 47.89×10^{-3}	kN/m^2	20.88
1 hundredweight per square foot	cwt/ft^2	5.36	kN/m^2	0.1864
WORK, ENERGY 1 foot pound	ft lb	1.356 joules (or newton metres, Nm)	J	0.7375
POWER 1 horsepower	hp	0.7457 kilowatts (kJ per second)	kW	1.341

Notes

1. British Imperial units will be found in old documents, maps, site and building plans and detail drawings. For interpretative purposes, note that iron structures were generally 'built' to units of feet and inches.

2. 9.81 metres per second per second (m/s^2) is the acceleration due to gravity. When indicating forces rather than masses, the units pound-force (lb-f) or ton-force are strictly correct, although the word force is often taken for granted and not written.

3. Rounded conversion factors are derived from those shown in bold. For a more complete listing of British Imperial weights and measures refer to the web site of the National Weights and Measures Laboratory, www.nwml.gov.uk Conversion factor calculators are available on the useful 'engineering fundamentals' subscription web site www.efunda.com

PAGE	DATE	STRUCTURE	GRID REF	LISTING	HBNUM	NMRS no.	Site or Works	Location	Figures (final draft)
Public, Commercial and Residential Buildings									
43	c.1839	The Town House Hotel, Royal Crescent, Glasgow	NS57286606	B		NS56SE 1702		72/4/6 Queens drive, Royal Crescent, Glasgow	74
45,112	1846	United College, St Andrews University	NO 5102 1687	B	40772	NO51NW 258	St Andrews University	United College, St Andrews University	77
5,6	1854	The Old Fruitmarket, City Halls, Glasgow	NS 5963 6514	A		NS56NE 4821	Candleriggs City Hall and Bazaar	Albion Street Glasgow	12,13
119,126,142	1855	A Gardner & Son's Furniture Store, Jamaica St., Glasgow	NS 5879 6502	A	33065	NS56NE 73		36 Jamaica Street/ 10 Midland Street, Glasgow	186
7	1858	Holmwood House, Cathcart, Glasgow	NS 5851 5969	A	33944	NS55NE 24		61,63 Neterlee Road, Cathcart, Glasgow	
7,8	1859	St Vincent Street Church, Glasgow	NS 5831 6555	A	33150	NS56NE 235		St Vincent Street Church, 261 St Vincent Street, Glasgow	14,15
102,165	1859	Edinburgh Post Office, Edinburgh	NT 2591 7396	A	29899	NT27SE 485		Waterloo Place Edinburgh	156,227
105	c.1860	shop front, Glasgow Green							
56	1861	The Royal Museum, Chambers Street, Edinburgh	NT 2585 7333	A	27748	NT27SE 462.00		44 Chambers Street, Edinburgh	89
136-7	1868	Morgan Academy, Forfar Road, Dundee	NO 4132 3180	A	25288	NO43SW 186		Forfar Road, Dundee	205a,205b,205c
48	1874	Edinburgh Royal Infirmary	NT 2560 7303	A		NT27SE 480.01	Various sights listed	Edinburgh	80
104	1875	shop front, The Grassmarket, Edinburgh	NT 2548 7335	B	43496			Edinburgh	159a
105	1875	126-136 Ingram Street, Glasgow	NS 5949 6523	B	32742	NS56NE 165		126-136 Ingram Street, Glasgow	159c,159d,
163	1877	remodelling at Callendar House, Falkirk	NS 8986 7934	A	31236	NS87NE 3.00		Callendar House, Falkirk	224
134	1878	Dunblane Hydro	NN 7881 0157	B	26409	NN70SE 98.00		Dunblane	
71	1896	Langside Hill Church, Langside Road, Glasgow	NS 5780 6171	B	32358	NS56SE 111		22 Langside Road, Glasgow	118
48-9,159	1897	McEwan Hall, Edinburgh University	NT 2579 7311	A		NT27SE 475.00	Teviot Row, Bristo Square, University of Edinburgh	Edinburgh	81
49	1900	Atlantic Chambers, Hope St/ Cadogan St, Glasgow	NS 5867 6524	A	33050	NS56NE 662		43,45,47 Hope Street, 1A Cadogan Street, Glasgow	
49	1902	Scotsman Building, 20-36 North Bridge, Edinburgh	NT 2588 7373	B	30143	NT27SE 460		20-36 North Bridge, Edinburgh	
Bridges									
59,60,61	c.1804	Linlathen East Bridge, Linlathen, Dundee	NO 4638 3285	A	25892	NO43SE 88	Over Dichty Water	Linlathen House/ Dichty Water, Linlathen, Dundee	93,94
61	1813	Duchess Bridge, Langholm, Dumfriess and Galloway	NY 3559 8523	A	9734	NY38NE 31	Over the River Esk	Langolm Lodge/ River Esk, Langholm, Dumfries & Galloway	
3,61	1815	Telford Bridge, Craigellachie, Aberlour, Moray	NJ 2853 4519	A	2357	NJ24NE 15	Over the River Spey	Craigellachie/ River Spey, Aberlour, Moray	10
61	1817	John S Brown suspension bridge	Not in Canmore						99
64,100	1820	Union Suspension Bridge, Scottish Borders	NT 9340 5103	A	13645	NT95SW 2	Over the River Tweed	Hutton Parish/ River Tweed, Scottish Borders	154
61	1821	Almond Aqueduct, Union Canal, Edinburgh	NT 1048 7062	A	7371	NT17SW 47	Over the River Almond	Kirknewton Parish	97,98
64,65	1822	King's Bridge, Glasgow		demolished				Glasgow	106
66,157	1831	Braid Burn Railway Bridge, Edinburgh	NT 2862 7808	B	27949	NT27SE 553	Over Braid Burn	The Innocent Railway, Braid Burn, Edinburgh	107,108
65	1831	Wellington Suspension Bridge, Aberdeen	NJ 9430 0497	A	20073	NJ90SW 28.00	Over the River Dee	Craiglug/ River Dee, Aberdeen	
61	1832	Old Spey Bridge, Fochabers	NJ 0397 2633	A	15645	NJ340594	Former military and road bridge over the Spey	Grantown on Spey	
63	1837	St Devenick Suspension Bridge	NJ 8977 0260	A		NJ80SE 43	Carried a foot bridge over the river Dee	Peterculter, City of Aberdeen	101
67	1841	Carmunnock Road Bridge, Glasgow	Not in Canmore				Polloc & Govan Railway		111
65	1850	Roxburgh Viaduct Footbridge	NT 7020 3041	B		NT73SW 63	Carried Kelso branch line over river Teviot	Roxburgh, Scottish Borders	103
71	1854	Park Bridge, Aberdeenshire	NJ 9371 0424	A		NJ90SW 31.10	foot bridge over upper lake, Duthie Park	Aberdeenshire	117
63-4	1854	Bridge of Oich	NH 3376 0361	A	1872	NH337036	Over river Oich	Abercalder, Inernesshire	104,105
63,65	1856	St Andrews Suspension Bridge, Glasgow	NS 5990 6400	A	33692	not in CANMORE	Over the River Clyde	Adelphi St/ Glasgow Green/ River Clyde, Glasgow	102
67,69	1857	Balmoral Bridge	NO 2621 9492	A		NO29SE 10	Suspension footbridge, Balmoral Castle	Balmoral Castle, Braemar	
66	1857	Girder Bridge, Inverythan		collapsed			Great North of Scotland Railway		109
67	1858	Findhorn Railway Viaduct, Forres, Moray	NJ 0207 5868	A	8690	NJ05NW 102	Over the River Finhorn	River Findhorn/ Greshop, Forres Parish, Moray	110
68	1863	Dalguise Railway Viaduct, Perth and Kinross	NN 9948 4791	A	11117	NN94NE 13	Over the River Tay	River Tay, Little Dunkeld Parish, Perth and Kinross	112
8,60,61,142	1863	Carron Bridge, Moray	NJ 2245 4116	A	8495	NJ24SW 14	Over the River Spey	River Spey, Knockando Parish, Moray	95,96
68,69,70	1874	Bilston Viaduct, Midlothian	NT 2817 6484	A	13035	NT26SE 83	Over Bilston Burn	Bilston Burn, Lasswade Parish, Midlothian	113
5,8	1887	Tay Railway Bridge, Dundee	NO 3910 2800	A	25681	NO32NE 11	Over the Firth of Tay	Dundee	2
5,41	1890	The Forth Bridge,Fife	NT 1382 7817	A	9977	NT17NW 70	Over the Firth of Forth	Inverkeithing Parish, Fife	
	others								
	1830	Haugh of Drimmie Suspension Bridge	NO 1700 5021	A	19830	NO15SE 45	Over the River Ericht	Glenericht Lodge, Rattray Parish, Perth & Kinross	
	1871	Portland Suspension Bridge	NS 5891 6474	A			Over the River Clyde	Clyde St/ Portalnd St/ River Clyde, Glasgow	
	1871	Boatford Suspension Bridge	NY 3623 8452	B	37139	NY38SE 53	Over the River Esk?	Langholm, Dumfries and Galloway	
	1897	North Bridge	not in Canmore	A	30035			Edinburgh	
	1900	Suspension Bridge	NO 7016 9472	C(S)	3253		Over River Feugh	River Feugh/ Feugh Lodge, Banchory-Ternan Parish, Aberdeenshire	
	1913	Port-Na-Craig Suspension Bridge	NN 9400 5766	B	39858		Over River Tummel	Port-Na-Craig, Pitlochry Burgh, Perth and Kinross	
	1866	Seabraes Mill		not built				Dundee	228
	1866	Speirs Wharf	NS 5884 6677	B	33620	NS56NE 119	Port Dundas Sugar Refinery	40 - 50 Speirs Wharf, Glasgow	
	1873	Jute Spinning Mill	NO 4137 3113	B	24931	NO43SW 96.00	Taybank Works	62 Arbroath Road, Dundee	
	1839	The Coffin Mill, Logie Works, Dundee	NO 3917 3042	A	24956	NO33SE 61	Logie Works	205 Brook Street, etc., Dundee	46
	1855	Eglinton Engine Works	NS 5830 6430	A	33504	NS56SE 102		27,57 Cook Street/ 181-3 West Street, Glasgow	
	1871	Marine Engine Works	NS 5478 6593	A	33357	NS56NW 36.00	Fairfield Shipbuilding Yard and Engine Works	1048 Govan Road, Glasgow	
		Glasgow Tramway's Dept., Coplawhill Works	NS 5802 6292	demolished		NS56SE 993	Brick works	Strathbungo, Glasgow	71
		Gilmorehill Building	NS 5687 6666			NS56NE 992	University of Glasgow	Glasgow	
		Strathleven House	NS 3960 7811			NS37NE 36.00		Strathleven House, West Dunbartonshire	
		The American Express Building	NT 2473 7372			NT27SW 199		Princes Street, Edinburgh	
		Edinburgh hotel balcony							210
		Street of Edinburgh hotel							220
		Jim Winning's Glasgow Railings							211
	1846	Victoria Swing Bridge	NT 2698 7669	B	27061	NT27NE 61	Leith Docks	Old East Dock, Leith, Edinburgh	
	1834	Crathie Suspension Bridge, Aberdeenshire	NO 2659 9424	A	2988	NO29SE 8	Over the River Dee	Crathie & Braemar Parish/ River Dee, Aberdeenshire	