

Iron and steel bridges:

condition appraisal and remedial treatment

Prepared under contract to CIRIA by Gifford WSP

G P Tilly	Gifford
S J Matthews	WSP
D Deacon	Steel Protection Ltd
J De Voy	Gifford
P A Jackson	Gifford



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Classic House, 174-180 Old Street, London EC1V 9BP

TELEPHONE 020 7549 3300 FAX 020 7253 0523

EMAIL enquiries@ciria.org

WEBSITE www.ciria.org

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Tilly, G P, Matthews, S J, Deacon, D, De Voy, J, Jackson, P A

CIRIA

C664 © CIRIA 2008 (revised) RP721 ISBN: 978-0-86017-664-0

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library.

Keywords Transport and infrastructure, facilities management, health and safety, knowledge management, materials, materials technology, regulation, site management, sustainable construction, whole-life costing	
Reader interest Asset management, maintenance and upgrading of iron and steel bridges	Classification AVAILABILITY Unrestricted CONTENT Advice/guidance STATUS Commissioned, committee-guided USER Asset managers, designers, contractors, owners

Published by CIRIA, Classic House, 174–180 Old Street, London, EC1V 9BP

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Summary

This book aims to meet the requirements of those having a general knowledge of bridge engineering and asset management but requiring information about the performances and specific requirements of iron and steel bridges.

In the UK there are some 22 000 iron and steel bridges. They have a very important role as part of the infrastructure and need to be maintained to meet modern requirements of strength and serviceability which, in most cases, far exceed what was considered in their original design. Many are heritage listed as they have great significance in industrial history, for example Ironbridge in Shropshire, and their maintenance is subject to requirements of legislation.

The historic development of materials, from cast iron to high strength steel, is described as it is important to have this knowledge when managing and assessing bridges of varying ages. For the same reason, the development of structural form is described, from the early arches having connections developed from carpentry, to modern stiffened plated construction having welded joints.

Guidance is provided on the relevant statutory requirements that must be followed in the care and maintenance of bridges as these have a profound effect on design and planning of projects.

Asset management is explained, including bridge management systems, preventative maintenance, and best practice.

The defects and processes of deterioration that typically occur in iron and steel bridges are described and illustrated by photographs.

There are substantial sections on inspection, testing and monitoring. These explain the strategies of inspection, the range of available laboratory and field tests, and methods of monitoring the behaviour of bridges as an aid to diagnosis or surveillance preceding remedial action or replacement.

Methods of structural assessment, from low-level appraisal to non-linear analysis, are given. Topics considered include: codes of practice, treatment of damage and deterioration, management of under-strength bridges, and financial liability.

The design and execution of remedial works are considered in three sections; general principles, repair, and strengthening. Repair is considered as the restoration of a structure to its design strength (or serviceability), strengthening is concerned with raising the load carrying capacity to above the original design value. Strengthening projects have been mainly concerned with the older bridges but also include more recent bridges such as the Docklands Light Railway. The examples described are of rail, canal and highway bridges.

Protection of iron and steel from corrosion is crucial to long life and low maintenance. The historic development of paint systems and current health and safety issues are described. There are sections on modern systems of protection, including inspection and repair, and treatment of ironwork, buried structures and complex configurations.

Acknowledgements

The authors acknowledge information kindly provided by Ed Proctor (Nuttall), Derek Hughes (Taylor Woodrow), Simon Clubley (Mott MacDonald), Martin Lorrimer (Dundee City Council), Ian Chapman (TfL), Pat Warrenner (Hampshire County Council), Graham Slade (WSP), Tony Oakhill (Gifford), Will Duckett (Gifford), Barry Mawson (Rtd) and John Holly (EH Services Ltd).

A significant contribution to Chapter 6 was made by Dr Martin Ogle (TWI).

Project funders

The need for this work was identified by the Bridge Owners Forum. CIRIA and the Bridge Owners Forum are grateful to the following for providing the funding for this project:

Bridges Board, Department for Transport
Network Rail
CIRIA Core Programme Sponsors
Transport for London
Health and Safety Executive
British Waterways

Research contractor

Gifford WSP

Authors

Graham Tilly BSc(Eng), DIC, ACGI, PhD, CEng, FICE

Graham is an emeritus director with Gifford. He has some 35 years experience in bridge engineering and research with expertise in materials, fatigue, whole life costing, and conservation. He has written some 80 papers and several books and was the lead writer of the guide.

Steve Matthews MSc DIC C.Eng FStructE MICE MIOD

Steve is senior technical director for WSP UK, bridges and civils. He has 30 years experience at home and overseas for public and private sector clients, working for large multidisciplinary and small specialist consulting engineers, steelwork fabricators, and research organisations. He specialises in structural steelwork, composite construction, design and construct and bridge management.

Paul Jackson BSc PhD CEng FICE FStructE

Paul is a Gifford technical director with 30 years experience of bridge design, analysis, construction and research and he serves on bridge code committees. He has particular expertise in assessing the real strength of structures. His main contribution was in the assessment of structures.

Julian De Voy, BSc PhD CEng MICE

Julian De Voy, formerly a Gifford associate, has more than 15 years' practical experience of planning and undertaking inspection, testing and strengthening contracts on metallic structures. He contributed the section on inspection. Julian is now a technical manager with Grontmij, Solihull.

David H Deacon CSci, FICorr (Hon), FTSC

David is a director of the Steel Protection Consultancy and has had 40 years experience as a paint technologist. He has been employed on the Forth Road and Rail Bridges, Tower Bridge, Blackfriars, Southwark, Hammersmith and Lambeth Bridges in Central London, as well as bridges in Asia and the Middle East. He contributed the section on coatings.

Steering group chair

Mr J Clarke (chair)	BRB (Residuary) Limited
---------------------	-------------------------

Steering group

Mr D Ashurst	Arup
Mr B Bell	Network Rail
Mr G Bessant	TfL
Mr P J Brown	Oxfordshire County Council
Mr E Bunting	Department for Transport
Mr M Bussell	Arup
Mr M Collings	Gifford
Mr K Duguid	Transport for London
Mr A Ghose	Faber Maunsell Ltd
Mr G Kerr	HSE (Railway Inspectorate)
Mr M Holford	Severn Trent Water
Mr R Howe	British Waterways
Dr. R.J. Lark	Cardiff School of Engineering
Mr C Mayer	Stoke City Council
Dr J Menzies	Independent Consultant
Mr A Monnickendam	Cass Hayward LLP
Mr T Swailes	University of Manchester
Mr I Wesley	Atkins
Mr T Wilkins	Mott MacDonald

CIRIA managers

Miss S Connolly	Project manager to April 2007
Mr K N Montague	Project director

Photographs

Photographs have kindly been provided by the authors' organisations or by members of the Steering group.

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* Bridge recognised nationally as having special historic significance

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Glossary

Bridge deck	Superstructure including running surface and excluding beams when separate.
Brittle fracture	Cleavage fracture which occurs in body centred cubic structures on (100) crystallographic planes. Brittle fractures have negligible ductility and energy absorption.
Cementite	Hard constituent of white cast iron, an iron carbide, Fe_3C .
Characteristic strength	Mean strength less 1.64 standard deviations.
Faying surface	Connecting faces between steel plates in a bolted joint.
Ferrite	Pure iron.
Graphite	A form of carbon.
Graphitisation (graphitic corrosion)	Corrosion of grey cast iron in which the metallic iron is converted into corrosion products leaving the graphite intact.
Hoggin	Well graded gravel having clay binder. Historically used for tracks and paths but also sub-pavement over jack arches.
Half through bridge	A bridge in which the lower chord carries the vehicular or pedestrian traffic.
Huck bolts	Proprietary bolt.
Macalloy bars	High strength steel bars commonly used for prestressing.
Pearlite	A layered structure having a pearl-like appearance under the microscope and composed of cementite and ferrite.
Prepreg	Pre impregnated fibre. Resin impregnated cloth, mat or filament in flat sheet. The resin is often partially cured to a tack-free state.
Repair	Restoration of a structure to its design strength.
Scoria	Larva-like material used for filling (bodging) defects in cast iron.
Slag	A by-product in the manufacture of iron and steel.
Strengthen	Increase the load carrying capacity of a structure to above the design value.
Stringer	Bands of slag aligned in the direction of rolling wrought iron.
Through bridge	A bridge in which the lower chord carries the vehicular or pedestrian traffic and having cross-bracing located above the traffic.

Abbreviations

ACFM	alternating current field measurement
ACOP	approved code of practice
ACSM	alternating current stress measurement
BMS	bridge management system
CDM	construction, design and management
CFRP	carbon fibre reinforced polymer
ECA	engineering critical assessment
FRP	fibre reinforced polymer
HAZ	heat affected zone
HSE	Health and Safety Executive
HSFG	high strength friction grip
ICATS	Industrial Coating Applicator Training Scheme
ILO	International Labour Organisation
LVDT	linear variable differential transducer
MIO	micaceous iron oxide
MPI	magnetic particle inspection
NDT	non destructive testing
NIOSH	National Institute for Occupational Safety and Health
OES	optical emission spectrometry
PTFE	poly tetra fluoro ethylene
RSJ	rolled steel joist
SAC	special area for conservation
SSSI	site of special scientific interest
STRA	short transverse reduction in area
TCB	tension control bolts
TIG	tungsten inert gas
UC	universal column
UHM	ultra high modulus (CFRP)
UIT	ultrasonic impact testing
UP	ultrasonic peening
UTS	ultimate tensile strength

Units

1 inch	=	25.4 mm
1 foot	=	304.8 mm
1 pound force	=	4.448 N
1 ton force	=	9.964 kN
1 lb/in ²	=	0.0069 N/mm ²
1 ksi	=	6.9 N/mm ²
1 ton/in ²	=	15.44 N/mm ²
1 micron	=	0.001 mm

1 Introduction

1.1 BACKGROUND

The infrastructure of the UK including road, rail, canal, docks, and footpaths, contains some 22 000 iron and steel bridges. These bridges range in size from single-span to multi-span viaducts and are constructed using cast iron, wrought iron and steel. They date from the oldest surviving iron bridge at Coalbrookdale built in 1779. Built in 1800, Coalport Bridge nearby continues to carry vehicular traffic (see Figure 1.1). Some 12 000 of the 16 000 rail bridges were constructed before 1914 and many exceed the notional design life of 120 years given in BS 5400. Many iron and steel bridges are heritage listed and require special treatment bound by legislation. In general they have performed well, particularly in light of the increased traffic loadings and intensities, but all require regular inspections, maintenance and some require strengthening. Many have received remedial work in the past, however this is often considered dated in the light of current knowledge. Correct application of modern state-of-the-art understanding of the behaviour of iron and steel bridges, and better maintenance and repair techniques, enables these vital structures to be kept in use for the foreseeable future.

Steel bridges built in the motorway era have been designed to more modern standards but many have required strengthening or widening to meet the requirements of increased volumes and weights of traffic.

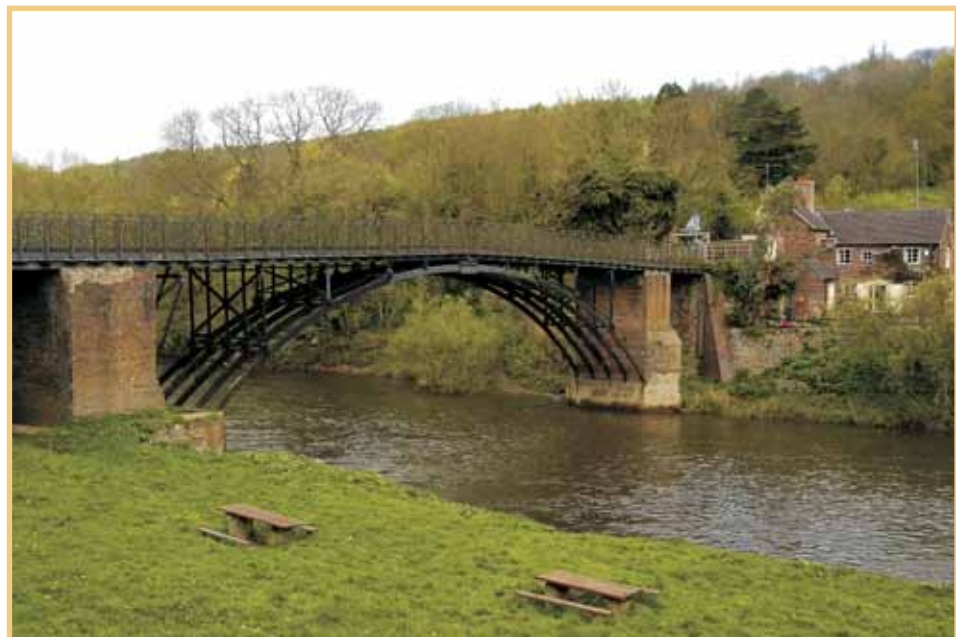


Figure 1.1

Coalport Bridge

It has been recognised that there would be benefit in drawing together into a single guidance note the combined knowledge of the principal bridge owners and engineers on the asset management of such bridges. Asset management in this context includes risk management, inspection, assessment, maintenance, repair and strengthening. Supportive tools include high level structural analysis, material testing, load testing and

monitoring. Many owners already have specific procedures drawn up over many years to suit the operational requirements of the organisation. Each set of procedures is broadly similar but varies in detail and emphasis.

Previous reports by CIRIA have provided best practice guidance on the condition appraisal, assessment and remedial treatment of infrastructure for embankments CIRIA C591 (Perry *et al*, 2003a), cuttings CIRIA C592 (Perry *et al*, 2003b) and guidance for the assessment and repair of masonry arch bridges CIRIA C656 (McKibbins *et al*, 2006). These projects have demonstrated that considerable benefits will arise from synthesising the asset management procedures of different owners into a common best practice approach for all such structures.

1.2 AIMS OF THE BOOK

This book builds on earlier CIRIA reports and is complementary to the guidance on masonry arch bridges, CIRIA C656 (McKibbins *et al*, 2006), which has many features and requirements in common. It aims to provide infrastructure owners, their designers, contractors, asset and maintenance managers with comprehensive, authoritative and impartial best practice guidance on all aspects of the asset management of iron and steel bridges.

This book aims to meet the requirements of those having a general knowledge of bridge engineering but requiring information about the performances and specific requirements of the appraisal and remedial treatment of iron and steel bridges.

Some of the more general aspects common to all types of bridge such as asset management, risk management and the regulations associated with health and safety, the environment and heritage that have been covered in the other CIRIA publications, are briefly introduced and referenced so that readers are informed of the generalities and can obtain more detailed guidance at source.

Use of this guidance will lead to cost savings through a reduction in the deterioration of iron and steel bridges, and increased confidence of owners to apply whole life costing with improved safety and cost-effective long-term management strategies to their bridge stocks. Moreover there are great benefits of sustainability to be obtained from the maintenance of existing structures and consequential savings of natural resources that would otherwise be consumed in reconstruction.

1.3 SCOPE

This book is concerned with single- and multi-span iron and steel highway, rail, canal and other bridges and viaducts of all ages and having spans of 2 to 50 m. It deals with the more common structural forms:

- arches
- box girders
- plate girders
- truss girders
- lattice girders
- through girders
- suspended bridges.

And decks:

- jack arch decks
- buckle plate construction
- infill decks
- trough decks
- longitudinal timber troughs
- orthotropic decks.

Most of these components relate to wholly steel bridges while others relate to composite construction having concrete, masonry or brickwork acting structurally with iron or steel.

The requirements of footbridges, demountable bridges and movable bridges are considered within the aforementioned types. Unique bridges, for example transporter bridges and long-span bridges (spans greater than 50 m), are not considered.

This book deals with iron and steel bridges which are the most dominant metal bridges in the UK. The very few (single figures) aluminium bridges in the UK are described in Appendix A1.

1.4 ISSUES OF SPECIAL IMPORTANCE TO IRON AND STEEL BRIDGES

Topics of particular importance in the management of iron and steel bridges include:

- the need to understand the construction materials, their properties (including variability) and behaviour
- the need to understand the regimes of built-in stresses and their influences on overall behaviour
- the characteristics of brittle fracture and fatigue in relation to iron and steel
- the process and development of corrosion, its potential effect on structural integrity, and interactive effects in promoting brittle fracture and fatigue
- the problems posed by older designs and modes of construction that are no longer in use
- protective systems, their characteristics and useful lives. The resistance of protective systems to environmental effects
- consideration of historic and aesthetic aspects of bridges and the requirements of heritage authorities for sensitive treatment of listed and scheduled bridges and their environs
- recognition of the aims of sustainable construction through maintenance of existing structures and minimal introduction of new materials.

1.5 HOW TO USE THE BOOK

The structure of the book is designed to be clearly laid out so that specific information can easily be identified. It reflects the various aspects of appraisal and remedial treatment.

Chapters 2 and 3 provide information about materials, construction and the regulations that dictate what can and cannot be carried out in relation to maintenance and construction operations on the bridges. It is important to be aware that statutory requirements are constantly being updated and it is necessary to ensure that the latest information is available.

Chapters 4 to 6 deal with assessment starting with information about the types of defect to be expected, methods of detecting defects including specialist techniques enabling removal of sample material while causing minimum damage to the structure. The different levels of structural analysis, supported by supplementary load testing, can be used to enable hidden strength to be identified.

Chapter 7 looks at structural assessment including preliminary and advanced methods of numerical analysis.

Chapters 8, 9 and 10 deal with the various construction operations, maintenance (both routine and preventative), repairs to defective components and strengthening.

Chapter 11 describes the types of protective system, preparation of the iron and steel, application of the protective system and performances.

Appendix A1 deals with aluminium alloy bridges giving examples, material properties, performances and the future potential for the material.

Appendix A2 provides case studies of repair and maintenance of iron and steel bridges. These include unsuccessful interventions as well as successes.

Appendix A3 gives information about the Industrial Coatings Applicator Training Scheme (ICATS) for the training and qualification of paint operatives.

Appendix A4 contains a bibliography of useful references grouped under:

- materials and structural forms
- assessment
- examples of repair and strengthening.

2

Materials and structural forms

In this chapter the historic methods of manufacturing iron and steel are described, and typical material properties are given.
The common structural forms of bridges and types of deck are outlined.

2.1

MANUFACTURE OF IRON AND STEEL

When carrying out an appraisal and planning remedial treatment for defective iron or steel bridges, it is important to have a full knowledge of the original materials, their manufacture, characteristics, performances and the way they have been used in construction. More detailed information on these topics has been provided by Bussell (1997), Tilly (2002) and Swailes (2006).

Dates when cast iron, wrought iron and steel were in common structural usage are given in Table 2.1.

2.1.1

Cast iron

It became possible to produce reliable cast iron in the early 1700s and one of the first iron bridges, Ironbridge in Coalbrookdale, was completed in 1800. In the manufacture of cast iron, the molten iron produced in a blast furnace was poured into a trough called a sow with offshoots called pigs, hence the term pig iron. It was customary to mix different varieties of pig iron from different localities to achieve what was considered to be an optimum mix for a particular use. Cast iron used for structural applications was invariably grey iron made from the best quality pig iron and considered to be the most reliable.

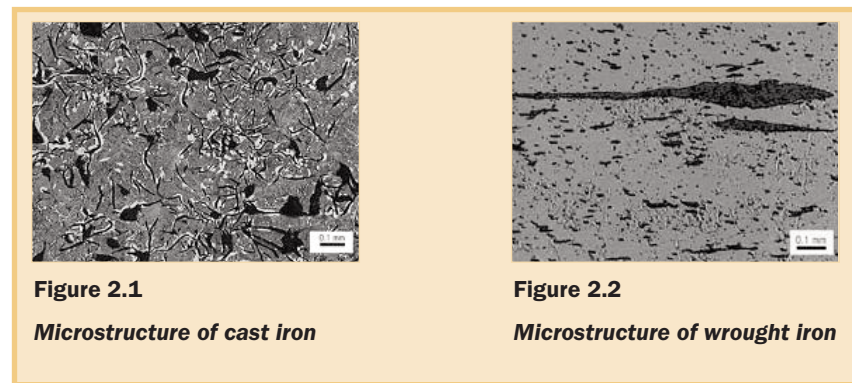
Cast iron contains typically two to five per cent carbon. In white cast iron the carbon is present as cementite and the fracture of such an iron has a white appearance. White iron was rarely used in bridge construction. In grey cast iron most of the carbon is present as flakes of graphite, the rest is in the form of pearlite or ferrite and the fracture is grey. As cementite is very hard, white cast iron is hard and brittle. Graphite is soft so that grey cast iron is less hard, readily machineable and less brittle.

The grey cast iron made nowadays is similar to the historic cast iron but made to higher standards, and has less variable properties. Ductile cast iron is a modern material with the graphite present as spherical nodules and properties similar to carbon steel.

Unsoundness of castings was a problem that remained throughout the era of cast iron bridges and there are well chronicled cases of failures caused totally or partially by draw (blow) holes, for example Inverythan railway bridge in 1882, Berridge (1969), and the better known Tay Bridge in 1879. The earlier collapse of Dee Bridge in 1847 led to cast iron being replaced by wrought iron in design of large girder bridges. Cast iron continued to be used for short spans and arch bridges.

Cast iron can be recognised superficially by the more rounded shape of its edge details, the characteristic appearance of its sand moulded surface texture, and greater thickness of flanges, typically 40 to 50 mm. When there is doubt and the identity of the material is needed, tests can be carried out as described in Chapter 6.

A micro-section of cast iron is given in Figure 2.1. For more detailed information about the properties of cast iron see Angus (1976).



2.1.2

Wrought iron

The puddling process where the molten iron was raked to ensure that it was uniformly exposed to oxygen enabled mixed iron and slag to be produced which could be hammered and rolled into bar. This puddle bar was cut into suitable lengths and piled into orthogonal layers to produce a 0.5 m cube of bars secured together by wire or thin bar. The cube was reheated to 1300°C, hammered and rolled into bar. This process was then repeated to produce *best bar*. Repeating the process again produced *best best bar*. Strength and ductility was improved each time the process was repeated as the stringers of slag were broken up to produce a finer dispersion with the fibres aligned in the direction of final rolling. Some banding of the matrix structure may still be retained and becomes evident in cases where the wrought iron corrodes. A micro-section of wrought iron is shown in Figure 2.2. This corrosion characteristic has a useful by-product as it enables wrought iron to be identified on occasions when there is doubt.

Wrought iron is composed of almost pure iron plus about one per cent slag. It was made in small batches and consequently had variable properties from batch to batch. This is a significant factor in modern assessment of strength. Wrought iron has a higher performance than historic cast iron, superior tensile strength and ductility. By the 1840s wrought iron was being produced in bulb channels and small I-sections. Later, it was extended to larger sections, riveted plate and lattice girders etc. The use of wrought iron for major bridges declined towards the end of the 19th century and the last major wrought iron bridge to be constructed was by Eiffel in 1884.

Wrought iron components were formed by rolling and are characterised by having constant cross-sections. They were in relatively short lengths and longer components required connections riveted with splices or cover plates.

2.1.3

Steel

Steel sections were available in limited sizes from 1850 but commercial supplies were very expensive. In Britain most of the native iron ores were phosphoric and production of steel from phosphoric ores became possible in 1878 when Thomas and Gilchrist invented the basic process which enabled the harmful phosphorus to be removed. The manufacture and quality of steel developed rapidly and by 1887 Dorman Long had produced a standardised range of beams and other products. The first major steel bridge in Britain, the huge Forth rail bridge, was constructed in 1890 using building techniques and workers imported from nearby shipyards.

Steel derives its mechanical properties from a combination of chemical composition, heat treatment and manufacturing process. Steel can contain up to 2.5 per cent carbon, above this value the material is classed as cast iron. Alloying of carbon to iron increases its strength but lowers its ductility, for example a steel containing 0.4 per cent carbon may be twice as strong as pure iron. The early historic steels typically contained 0.2 to 0.5 per cent carbon. In later years structural steel was developed containing 0.1 to 0.25 per cent carbon providing an altogether better combination of strength and ductility.

Steel is cast into ingots and rolled to the required sections, and it has a more homogeneous structure than wrought iron.

Structural steels produced up to the 1950s were of poorer quality than current steels and were liable to contain defects such as laminations, deformities and inclusions. Early steels were also liable to brittle fracture due to having low fracture toughness and high brittle-ductile transition temperatures. Brittle fractures can typically initiate from stress concentrations and defects. With the introduction of welding in the late 1930s this was highlighted when a bridge at Hasselt in Belgium collapsed in March 1938 14 months after construction, at a temperature of -20°C. The fracture initiated at a defect in a weld.

The extent of the brittle problems became apparent when catastrophic brittle fractures occurred in the all-welded liberty ships during the 1940s. This led to an intensive programme of research through the 1950s, and the eventual improvements in the composition and manufacture of steel and welding processes.

The first welded bridge in Britain, Billingham Branch Line, was constructed in 1934 and although no longer carrying an active railway has survived to be used by pedestrians.

Table 2.1

Chronology of the use of iron and steel in bridges

Material	Approximate dates
Cast iron	1780 - 1900
Wrought iron	1810 - 1880
Steel	1880 - present

Weathering steels, introduced in the 1970s, have good resistance to corrosion and under favourable conditions do not require painting. These steels are high strength low alloy and have mechanical properties similar to grade S355 steels to BS EN 10025-1 (2004). Chapter 11 gives information about their performances under unfavourable conditions.

An example of a 15 year old bridge across rail having weathering steel beams is shown in Figure 2.3.



Figure 2.3 *Bridge having weathering steel beams*

2.2 MATERIAL PERFORMANCES

2.2.1 Cast iron

Historic cast iron is relatively strong in compression but is brittle and weak in tension. It is liable to have numerous types of defect mostly produced during the casting operation, see Chapter 5.

Cast iron has a non-linear relationship between stress and strain due to the presence of graphite flakes and it follows that there is no clearly defined yield point, see Figure 2.4. The presence of graphite flakes in the micro-structure of cast iron causes the embrittlement; a defect-free cast iron would still be brittle.

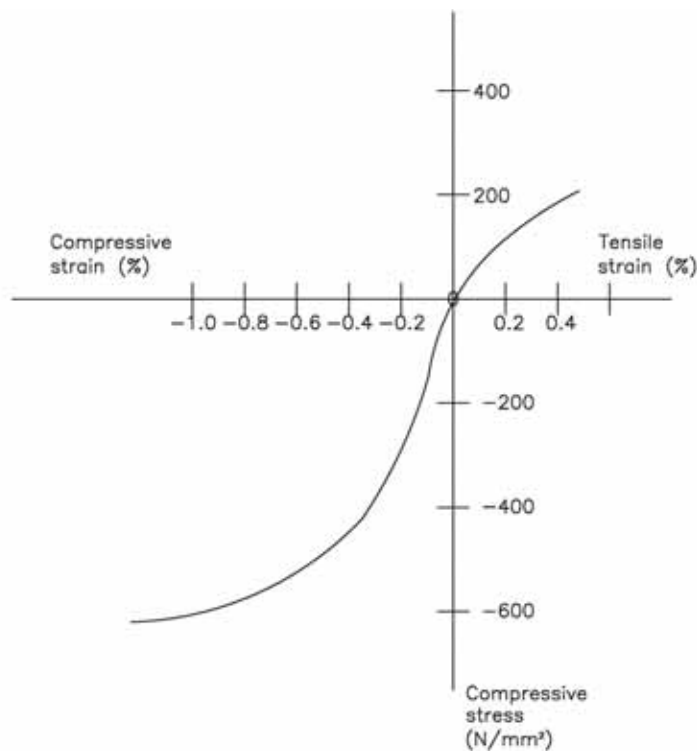


Figure 2.4 *Typical stress-strain relationship for historic cast iron, from Bussell (1997)*

Early cast iron I-beams having equal top and bottom flanges were used in bridges up to the 1840s. In many cases the beams were proof loaded to stress levels close to ultimate strength. Beams with bottom flanges three or four times bigger than the top flanges were widely used from the 1830s onwards when the relative strengths in tension and compression were better understood.

During the years 1830 to 1850 many combinations of cast iron and wrought iron were used in efforts to compensate for the shortcomings of cast iron in tension.

Modern cast iron containing spheroidal graphite is ductile in both tension and compression and can be used as a substitute for historic cast iron when it is necessary to raise the performance of the component in question, for example for parapets.

Cast iron has good resistance to corrosion evident in Figure 2.5.



Figure 2.5

Cast iron bridge after some 50 year weathering without maintenance

2.2.2

Wrought iron

In wrought iron, the stringers are aligned in the plane of a plate or the axis of a rod and cause the material to have anisotropic properties, the strength perpendicular to the stringers is about two thirds of the strength parallel to the stringers. Depending on the degree of working received during manufacture, corrosion of wrought iron plates can sometimes occur in planes adjacent to the stringers causing the material to delaminate.

Wrought iron has good ductility of ten per cent or more.

The research and preparatory work carried out by Robert Stephenson and his collaborators, Fairbairn and Hodgkinson, in support of the designs of the bridges crossing the River Conway and the Menai Straits not only defined the properties of wrought iron for years to come but represented one of the most significant achievements in engineering design. Their investigations included buckling, bending, deflection, friction of riveted connections, fatigue, wind forces and temperature effects. Conway Bridge was completed in 1848 and load tests were carried out to confirm the design. Britannia Bridge was completed two years later.

A particularly notable fatigue investigation was carried out by Fairbairn on riveted beams fabricated from wrought iron plate and angle-irons. The beams were 6.7 m long and 0.4 m deep. The tests were in repeated-bending involving up to three million cycles per beam and ran from March 1860 to January 1862. The object was to verify the maximum design stress of five tons per square inch (77 N/mm^2) which was applied for many decades to the design of iron and subsequently mild steel structures, Fairbairn (1864).

In the 1950s about 1000 rail bridges with wrought iron beams were identified by the former British Railways as being potentially at risk of fatigue failure. A number were in the course of being reconstructed or replaced and the opportunity was taken to test the redundant beams in bending fatigue. It was found that although the beams were of widely different manufacture and age, and wrought iron had variable properties from batch to batch (as indicated in Table 2.2), they gave consistent fatigue performances, specifically their fatigue limit. In the majority of cases it was concluded that this uniformity was probably because rivet holes in the beams tended to control crack initiation and subsequently fatigue life. The upshot of this programme was that very few wrought iron bridges had to be replaced on the basis of fatigue, McLester (1988).

Wrought iron has a lower resistance to corrosion than cast iron and is very poor in a marine environment, evident in the condition of Brunel's SS Great Britain when rescued for conservation in the 1970s.

2.2.3

Steel

Historic steels have variable ultimate tensile strengths which may typically be in the range 28 to 32 ton per square inch (432 to 492 N/mm^2). The earliest steels had an even wider range of strengths due to the difficulties in controlling the percentages of carbon and trace elements. In the absence of specific data a characteristic (yield) strength of 230 N/mm^2 is recommended in BD 21/01 for steels produced before 1955. When more accurate values are required it is necessary to remove samples and carry out tests to determine strength and ductility, as described in Chapter 6. An indication of the influence of carbon content on strength and ductility is shown in Figure 2.6. Typical strengths of cast iron, wrought iron and steel are given in Table 2.2.

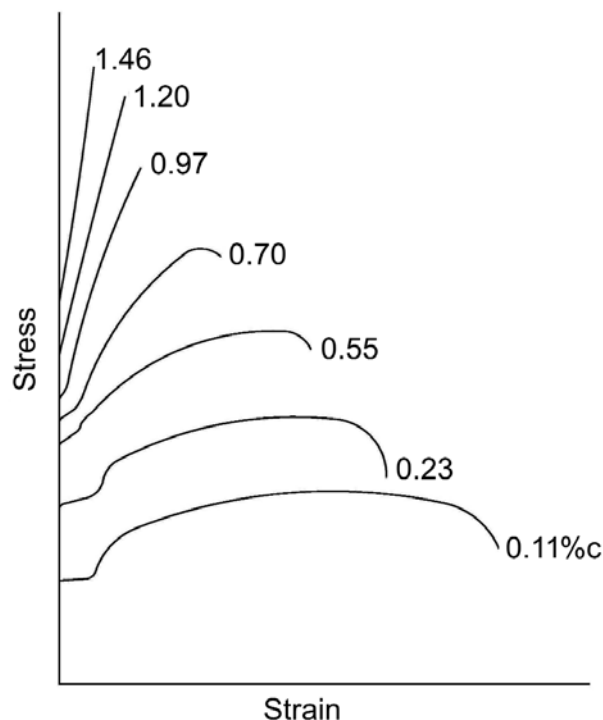


Figure 2.6
An indication of the influence of carbon content in steel

Historic steels are generally unsuitable for welding but wrought iron can be hot-welded in a forge (forge-welded). This is a difficult operation and should not to be attempted lightly.

Modern steels, having lower carbon contents, exhibit stress-strain relationships which have a clearly defined linear elastic region, upper and lower yield points, and a considerable ductile-plastic region prior to work-hardening, as shown in Figure 2.7.

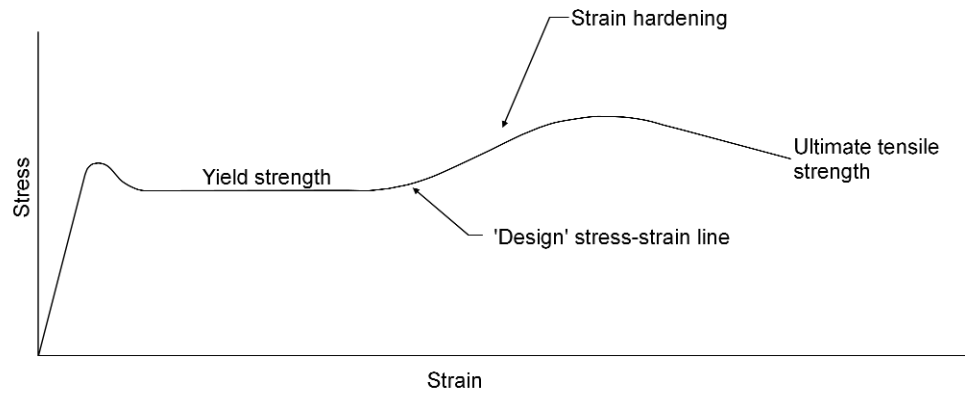


Figure 2.7 *Stress-strain relationship for modern steel*

Steel corrodes more readily than cast iron and requires regular painting. Exposed steel corrodes at a rate of about 0.05 mm loss of thickness per year in a rural environment and 0.05 to 0.1 mm in an industrial environment. It should be noted that heavy accumulations of rust do not necessarily indicate significant losses in sections because general rust (fully oxidised iron as opposed to local corrosion) occupies up to 10 times the volume of original material.

Table 2.2 *Typical ranges of UTS*

Material	UTS range N/mm ²
Structural grey cast iron	65 - 100* Lowest
	150 - 280* Highest
Wrought iron	278 - 593*
	309 - 386 BS 51 (1939)
Structural steel	432 - 492 BS 15 (1906)
	494 - 602 BS 968 (1962)

* data from Twelvetrees (1900)