CFRP strengthening of cast and wrought iron structures

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ABSTRACT: This paper addresses the rehabilitation of historic structures fabricated from cast and wrought iron using advanced fibre reinforced polymer composites (FRP). An historical perspective and a brief description of the metallurgy of both metals are outlined. Then a case study of the strengthening of large cast iron struts is presented together with some of the underpinning research. Finally research into wrought iron strengthening is discussed. The conclusion drawn is that rehabilitation using FRPs is feasible for both metals but various practical matters must be taken into account.

1 INTRODUCTION

Much of the railway infrastructure in the United Kingdom (UK) was constructed during the great railway expansion in the reign of Queen Victoria. In many cases it is nearly 150 years old. Many structures on the London Underground are made of cast iron and on the main railway system there are several thousand bridges fabricated from wrought iron. Often these structures are so strategic that their replacement would cause unacceptable disruption, yet they need rehabilitation to allow them to be used safely in the future. This paper will discuss the upgrading of cast and wrought iron structures using carbon fibre reinforced polymer composites (CFRP) as experienced in the UK. It will present a case study and also the research which has been undertaken to provide the technical justification which underpins the use of CFRP. Although the paper will concentrate on UK practice many of the issues presented will be of interest to engineers in the rest of the world.

2 AN HISTORICAL PERSPECTIVE

The use of structural cast iron developed at the end of the 18th century. The development of the railways from the 1820's required large numbers of bridges most of which were originally made of cast iron. Cast iron has serious limitations as a structural material as will be discussed later. Wrought iron was produced in industrial quantities from the late 1840's following Henry Cort's invention of the puddling (stirring the molten metal to mix in oxygen)process, and took over from cast iron as a higher performance material. It was common to use the more expensive wrought iron in tension or bending members with cast iron for the compression members. However, following the collapse of the Dee Bridge in 1847 wrought iron replaced cast iron for railway bridge construction. Steel was produced commercially by the Bessemer process from the 1860's but it is rare to find it used in structures completed before 1890. By 1900 steel was the only ferrous metal used in construction.

3 THE NATURE OF CAST AND WROUGHT IRON

3.1 Cast Iron

Cast iron is an alloy of iron containing 2.5 – 4% by weight of carbon and other impurities such as silicon, phosphorous, manganese and sulphur. The high carbon content lowers the melting point so it is ideal for casting. After placing in a sand mould it is cooled slowly. It is weak and brittle in tension and exhibits a significant size effect. Old cast iron suffers from various defects produced during casting:

- blow-holes up to 10mm diameter
- residual stresses and weaker, coarser material in the centre due to differential cooling
- large slag inclusions from impurities
- contamination from sand that detached from the mould
- cold joints, due to interruptions during casting
- large variations in section dimensions.

It has a non-linear stress-strain response which is different in tension and compression as shown in Figure 1. Since it was such an unreliable material design stresses were kept low, usually within the approximately linear regions of the stress-strain curve. The resulting sections were usually heavy with large tension flanges and small bulbous compression regions to resist buckling. Cast iron has good corrosion resistance because the silica in the moulding sand coats the metal surface. However cut or damaged surfaces corrode rapidly.

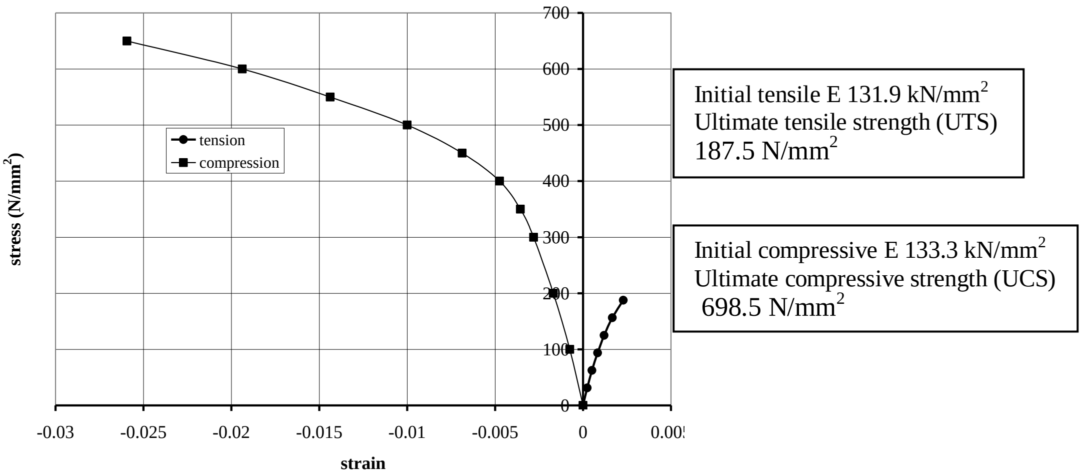


Figure 1. Typical stress-strain curves for early cast iron

3.2 Wrought Iron

Wrought iron is a mixture of very pure iron with only about 0.02% carbon content and siliceous slag. It was produced from cast iron which had been melted and puddled (stirred) to expose it to oxygen, a process which removed many of the impurities. The mass was cooled until it became a semi-molten, pasty, iron/slag mixture which was split into balls weighing about 50kg. These were hammered into shape and rolled out into thin plate. The plate was reheated and folded and the process repeated several times to improve the uniformity of the material. The hammering and rolling squeezed out excess slag and drew the remaining slag into long thin fibres in the rolling direction. Six repetitions were found to produce the best quality material; further working removed so much slag that the iron became brittle, Kirkaldy (1863).

The slag fibres in the iron matrix give the wrought iron highly directional mechanical properties as shown in Table 1, and the repeated hammering and rolling give the metal a distinctive laminar structure as can be seen at the failure surface shown in Figure 2. The manufacturing process produced relatively thin material; the test results in Table 1 came from 160 year old 6mm-13mm thick plates from a demolished railway bridge at Llangammarch Wells, Wales. The web plates (6mm thick) were rolled alternately in two perpendicular directions to achieve more even properties. Wrought iron is a very variable material, especially when comparing material from different sources; the properties in Table 1 were obtained from at least 22 specimens. A survey of test results from 33 sources, Moy et al. (2009a), gave an average with-grain ultimate tensile strength of 348 N/mm^2 with a standard deviation of 36 N/mm^2 and an elongation of 15% with a standard deviation of 7%. The latter values in particular show the variability.

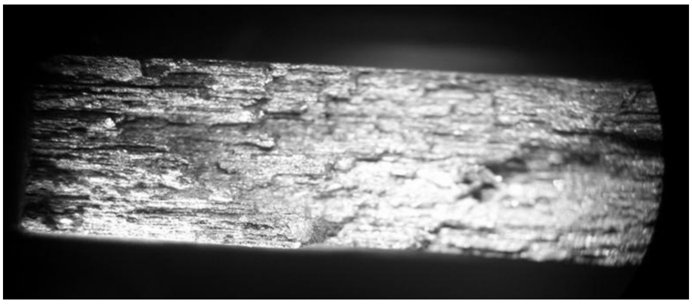


Figure 2. Photograph of tensile specimen failure surface showing the laminar structure of wrought iron

Table 1. Typical mechanical properties of historic wrought iron – University of Southampton specimens

	Property	with-grain	cross-grain	web
Tension	Strength (N/mm^2)	343	285	286
	0.2% proof (N/mm^2)	257	270	228
	Modulus (kN/mm^2)	215	241	190
	Elongation (%)	8.6	1.7	6.8
Compression	0.2% proof (N/mm^2)	206	-	-
	Modulus (kN/mm^2)	171	-	-

The wrought iron was produced in thin plate, angle or tee sections. It was a better material than cast iron, with good tensile and compressive strengths and reasonable ductility in the with-grain (slag fibre) direction. To fabricate large girders the thin components had to be hot riveted together as shown in Figure 3.

Wrought iron can be treated in a similar manner to steel although higher factors of safety must be used because of its greater inherent variability. However wrought iron is a fundamentally different material because of its laminar structure and the presence of the slag inclusions. These lead to the principal problem with the material; the possibility of delamination. The iron rusts but the slag does not, as a result the rust tends to detach itself in flaky sheets.

4 CFRP STRENGTHENING OF METALLIC STRUCTURES

Fibre reinforced polymer composites (FRPs) are used widely for strengthening concrete and steel structures. FRPs consist of carbon, glass or aramid reinforcing fibres embedded in a resin matrix. The most common resins in construction are thermosetting epoxies. Strength and stiffness are derived from the fibres while the resin protects and spreads load evenly amongst the fibres. Ultra-high modulus carbon fibres are generally the most suitable for metallic structures because they produce a composite with a higher elastic modulus than the metal, which gives the most efficient structural action. The process is now widely accepted in the UK and Design Guides are available, Moy (2001), Cadei et al. (2004).
The most common approach is to bond pultruded or 'prepreg' unidirectional CFRP plates to the

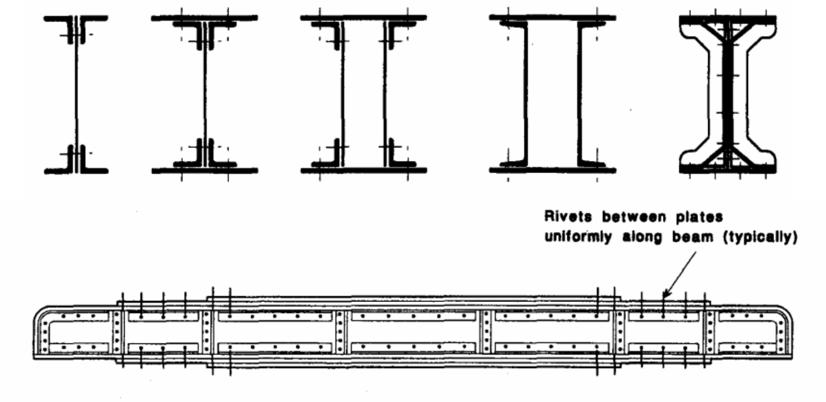


Figure 3. Typical cross-sections and elevation of wrought iron (Figures 3.7and 3.8 in Bussell (1975))

tension flange of the metal structure using an epoxy adhesive which cures at ambient temperature. The key to achieving satisfactory bond is the surface preparation of the metal substrate and in the UK gritblasting to the SA2½ industry standard is specified. Plate bonding works well for steel structures but, as shown below, may not be appropriate for cast or wrought iron, where the metal surface may be uneven or of poor quality. There are concerns about the possibility of galvanic corrosion of the metal since CFRP is a conductor, however the adhesive layer does provide some insulation and an insulating layer of glass fibre composite can be placed between the metal and the CFRP. Quality control is also an issue, being dependant on the supervision of the work and the procedures put in place by the contractor. In the UK specialist contractors almost always carry out the work.

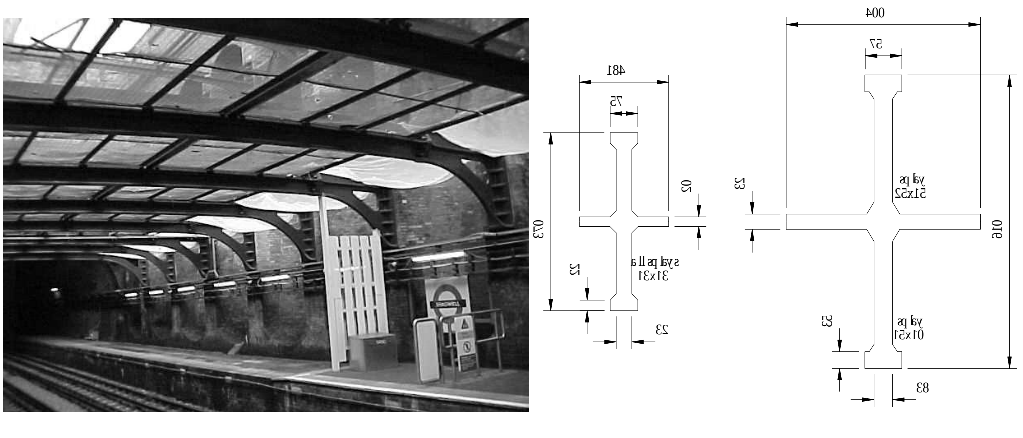
4 STRENGTHENING OF CAST IRON USING CFRP

A case study of the strengthening and stiffening of cast iron on the London Underground system is presented below. The structural configuration is unusual and illustrates many of the practical and technical issues that have to be addressed.

4.1 Vent Shaft V129

This shaft is located adjacent to Shadwell Station in the east end of London; Figure 4a shows the shaft from inside the station. The East London line was one of the earliest to be built and crosses the River Thames through Brunel's famous tunnel. When the line was constructed the trains were pulled by steam locomotives and it was necessary to remove exhaust smoke and steam from the tunnels using vent shafts, which are large brick lined holes from the surface down to the tunnel. To maintain the stability of the lining cast iron struts were placed across the vent shaft. At Shadwell there are a total of 18 struts placed at two levels, the lower nine being of larger cross-section. The upper and lower struts are 13m and 12.2m long respectively, their spacing is 3.35m, and cross-braces run between them. For most of their length the struts are of constant cross section but, as can be seen in Figure 4, there are elaborate 'shoes' at each end. Figure 4b gives details of the constant cruciform cross-sections of the struts.

Over the years there have been ground movements around the shaft which imposed load on the struts. It was not possible to measure the magnitude of these loads and they may have varied from strut to strut. When a cast iron strut is loaded in compression it bends due to casting imperfections, non-homogeneity of the metal and eccentricity of load. It was the regions of tensile stress caused by the bending that required strengthening because of the weakness of cast iron in tension, but it was impossible to determine the tensile regions of the in-situ struts so that all-over strengthening was necessary. The size of the struts and the arrangement of the vent shaft meant that it would not be possible to relieve the pre-existing load before strengthening was carried out.



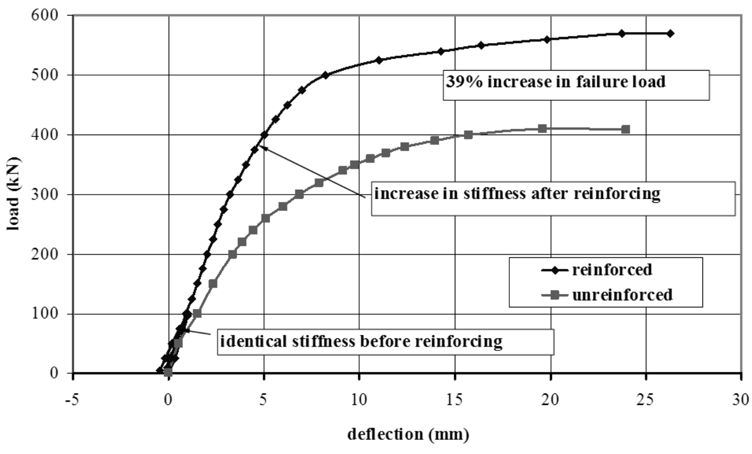
a) the lower struts at Shadwell b) dimensions of the in-situ struts

Figure 4. Cast iron struts at Shadwell

The cruciform cross-section was chosen originally because it is good in compression, the legs providing mutual bracing against buckling. Rehabilitation by the addition of steel would have been impossible; requiring complete replacement with new steel struts. An alternative was to use CFRP; although at the time this was an unproven technology.

The benefits of a strengthening scheme using CFRP had to be carefully assessed. Would there be any benefit from strengthening without load relief? Finite element analysis predicted that the CFRP in compression would fail first; would this have any effect on the strengthening of the tensile zone? Initial tests on full scale struts removed from another vent shaft [NEL, 1997] did not give clear guidance and a series of further tests were commissioned. Three pairs of scaled down struts were cast to the same recipe as the original cast iron and were tested. The three pairs gave ranges of slenderness ratio and load eccentricity. In two of the pairs one strut was

tested unreinforced and the other was tested after reinforcement with UHM CFRP plates. Different amounts of reinforcement were applied to the other pair. The reinforcement was applied while the struts were under an eccentric preload equal to 40% of the strength of the unreinforced strut. The tests, which have been extensively reported, Moy et al (2006), showed that there were worthwhile benefits from reinforcing with CFRP, in terms of increased stiffness and load capacity, even under significant preload. Figure 5 shows some typical results.
The strut tests demonstrated that the proposed CFRP strengthening would provide the required benefits and was technically feasible. There were practical considerations as well. The in-situ cast iron was covered in lead paint and although it was generally in good condition, the surfaces were poor due to blowholes and blemishes and there were significant geometric imperfections, preventing normal plate bonding. Surface preparation involved grinding off major surface blemishes, wet blasting to remove the paint, grit blasting, priming and filling the blowholes with epoxy filler. The CFRP had to be applied using the proprietary RIFT (Resin Infusion under Flexible Tooling) process, which involves vacuum infusion of the resin through the dry carbon fibres which are placed on the metal surface in a sealed bag. Bond is achieved through the adhesive property of the epoxy resin. The whole of each cruciform section was coated in CFRP, bonding to 160 surfaces with a total infused length of 880m. Up to 24 plies of UHM fibres were applied to each surface and the CFRP weighed a total of 1.8 tonne. The key to the success of the strengthening was the provision of a clean working environment and good site control. The project took 9 weeks with a team of 10 people. After the CFRP had cured it was painted white to reflect sunlight and minimise thermal stresses and movement. The struts were instrumented and are continuously monitored; they are still behaving as predicted.



Results for specimens III/U and III/R, preload of III/R 40% of III/U failure load.

Figure 5. Graph showing benefits of CFRP strengthening, even under significant preload

6 STRENGTHENING OF WROUGHT IRON USING CFRP

The laminar structure of wrought iron under load is potentially a problem when considering FRP strengthening, since delamination from inter-laminar shear would be a similar phenomenon to debonding of FRP at a metal/FRP interface. Research at University of Southampton, Moy et al. (2009b), addressed inter-laminar shear strength using the unique specimens shown in Figure 6 (note that the shaded region is the test surface). The minimum credible inter-laminar shear strength measured was 45.3 N/mm^2. A large number of specimens were tested because there was considerable variability in the results. It was found that abnormally low test results were due to

large slag inclusions within the test surface. The main conclusion was that minimum inter-laminar shear strength was a least double the shear strength of existing structural adhesives, allaying any fears of premature delamination.
As with cast iron it is the practicalities of CFRP strengthening that need careful consideration. Inspection of the existing structure is essential and corrosion in particular must be examined. If it is only surface corrosion as shown in Figure 7 the usual surface preparation before CFRP application will be adequate. If the corrosion is heavy with delamination it is essential to firstly address the cause of the corrosion. If the wrought iron is effectively continuously wet this must be remedied, if not corrosion will continue. Also the loss of effective cross section must be assessed to ensure that sufficient strengthening is applied. It is worth pointing out that steel should not be used to reinforce the wrought iron because it has a slightly different electro-potential to wrought iron and will corrode preferentially to the existing wrought iron.

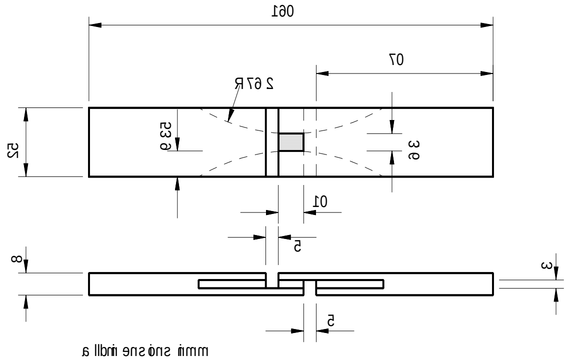


Figure 6. Interlaminar shear test specimens

Figure 7: Surface corrosion of wrought iron

The current UK Design Guide for CFRP strengthening of metallic structures, Cadei et al. (2005), specifically excludes strengthening of wrought iron due to concerns about possible delamination of the wrought iron. However, as reported above, research has shown that those fears are unfounded since the inter-laminar strength of wrought iron is at least double the shear strength of existing adhesives. Consequently the exclusion of wrought iron will be removed in the next edition, but currently there has been very little CFRP strengthening of wrought iron structures.
A practical problem that must be overcome is how to apply the CFRP around the rivets. Vacuum infusion is an obvious possibility since the application of the vacuum to the dry fibres will compress them around the rivet heads. Another possibility is to use ‘prepreg’ plates with glass fibres laid along the rivet lines. Holes could then be formed to an adequate depth in the glass fibres to fit over the rivets. Perhaps the easiest approach would be to use narrow strips of CFRP plate between the rivet lines and then bond full width plate across the flange.

7 SOME GENERAL POINTS

As with any FRP strengthening scheme certain general precautions are essential. The strengthening needs to be inspected regularly to ensure that it is functioning as required. Vandalism, including accidental vandalism from other contractors working on the structure, is a potential risk that must be minimised.

Temperature effects need to be carefully considered. The vent shaft struts can experience daily temperature changes of over 40°C. Suitable materials with glass transition temperatures above the anticipated maximum service temperature must be used. Fire protection is probably not required on external structures but they can be protected if necessary by intumescent paint.

8 CONCLUSIONS

The design of FRP reinforcing systems for historic structures fabricated from cast or wrought iron is not greatly different from that for steel structures. However it has been shown that the metallurgy of these metals and their resulting mechanical properties need to be considered at the design stage. Although cast iron generally needs to be strengthened when in tension it is not always possible to identify the regions of the structure or individual members that are in tension. In such cases the whole section needs to have FRP attached to it. Since it is usually not possible to relieve existing load on the original structure the strengthening scheme must be designed to allow for this. The good news is that testing has shown that even with a preload (modelling an existing load) FRP strengthening still provides many benefits. Testing has also shown that an initial failure of FRP under compression does not lead to instantaneous failure.

What singles out FRP strengthening of historic structures is the practical details. Surface preparation is as important as ever but more factors need to be addressed. The surface of cast iron has various imperfections. Protruding lumps of metal need to be ground off, blowholes need to be filled with epoxy putty. When casting imperfections are significant it will not be possible to attach a preformed FRP plate to the surface because the glue line will be unacceptably thick. Instead it is better to use the vacuum infusion process to form the FRP, relying on the adhesive properties of the resin to achieve bond. With wrought iron the problems are more to do with the lines of rivets connecting plates and sections together. Practical solutions to applying the FRP around the rivets are given in the main text above.

Various cast iron structures have been strengthened using CFRP and now that the reservations about FRP strengthening of wrought iron have been put to rest, it is likely that wrought iron structures will also be strengthened in the same way.

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