Full scale cast iron girders reinforced with CFRP - flexural testing

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ABSTRACT: This paper will report on the flexural testing of two cast iron girders from a demolished railway bridge in Scotland. The girders were 151 years old and had been reinforced with ultra high modulus carbon fibre polymer composite (CFRP) in 2004. The CFRP on one girder had been damaged during the demolition and was rendered completely ineffective before testing. The girders were 9m long and were tested in four point bending to failure giving a unique opportunity to compare the behaviour of unreinforced and reinforced cast iron at full scale. After the flexural testing fragments were tested to obtain material properties. The tests showed the considerable benefits of CFRP strengthening and confirmed that the CFRP was fully bonded to the cast iron until close to the point of failure. The test results have been compared to the original design predictions. The paper will include details of the girders, the test rig and procedure and will discuss the benefits obtained from CFRP strengthening of cast iron girders.

1 INTRODUCTION

The UK railway infrastructure, managed by Network Rail, has some 680 cast iron bridges. CFRP has been used to strengthen/stiffen some of these but the design of such schemes is largely theoretical with limited testing only on model scale specimens. Due to electrification, a 151 year old CFRP reinforced cast iron bridge on a line between Glasgow and Edinburgh in Scotland and located at Breich Station had to be demolished. Two of the main girders were removed intact although the CFRP on one was damaged. These presented a unique opportunity to determine the benefits of CFRP *at full scale*. Figure 1 shows the girder details. Brick jack arches resting on the bottom flanges spanned the gap between each girder. Different thicknesses of CFRP were applied to the girders but the test girders both had 14mm nominal thickness of CFRP. On Girder 1 the CFRP was damaged and was deliberately cut across to render it ineffective. On girder 2 there was limited damage to the surface veil of the CFRP but generally it was in good condition. The girders were 9m long overall and weighed about 4.5 tonnes. The CFRP scheme was designed by Consulting Engineers Tony Gee and Partners (TGP) and was installed in 2004. Although the girders were massive they were fragile and it was decided to limit transportation and to test them in Scotland. The only company in Scotland with the capacity for such testing was Doosan Babcock Limited in Renfrew near Glasgow. The author was commissioned by Network Rail, through the University of Southampton, to organise the testing.

2 POTENTIAL PROBLEMS IN TESTING THE GIRDERS

Cast iron is basically an iron alloy with a high carbon content (2.5% to 4% by weight) and other impurities. The high carbon content reduces the melting point making it ideal for casting. It is brittle in tension due to its coarse granular structure and the presence of large slag inclusions.

Tensile failure is sudden and catastrophic with significant energy release. Attention to safety during testing is essential, NEL (1998), Moy et al (1999, 2007).

In the 1800s girders were cast in sand moulds and the cast iron in large girders presents various problems: blow holes up to 10mm diameter, cold joints due to disruptions during casting, contamination from sand that detached during casting, large variations in section dimensions and differential cooling resulting in distortions in section geometry and residual stresses.

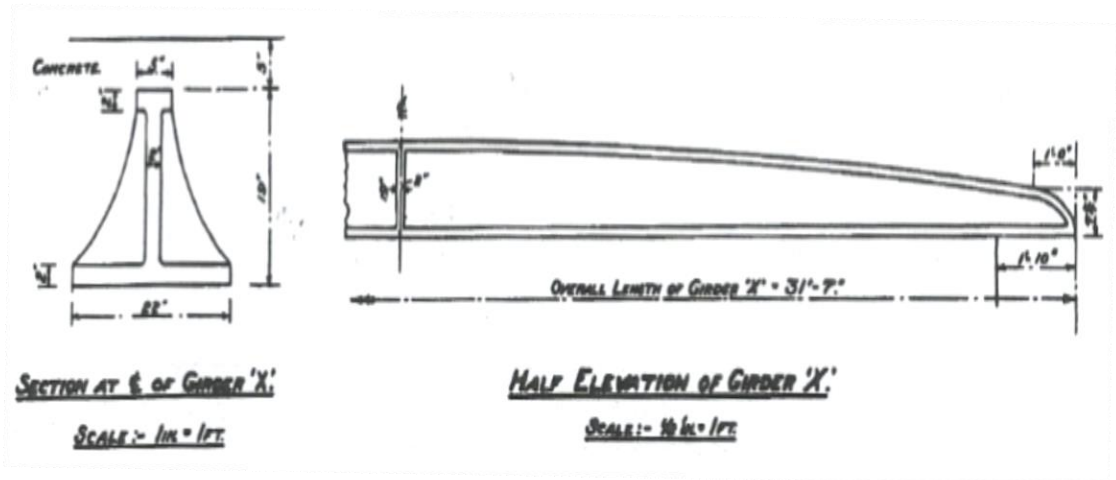

Figure 1. London Midland and Scottish Railway drawing showing cast iron girder details.

When the bridge was demolished it was found that fragments of the brick arches could not be removed easily. It was decided to leave the fragments in position to avoid damaging the cast iron. The weight of the fragments was minimal and did not affect the testing.

3 TEST SET-UP AND PROCEDURE

3.1 Test rig details

Figure 2 shows the test rig with a girder in position. The simply supported span of the girder was 8.49m. The rig was unusual in that hydraulic jacks applied upward forces at the ends of the girder with the specimen held against reaction frames at the third points. Doosan Babcock had to modify their standard rig to accommodate the specimens. Four-point bending gives constant bending moments and zero shear force in the middle third of the specimen and high shear forces and varying bending moments in the rest of the specimen. Network Rail assessments of the girders had shown adequate shear capacity so flexural failure of the girders was anticipated. However, the depth of the cast iron varied along the length so flexural failure would be expected close to the interior reaction points but the combination of high shear and bending moment just outside the middle third meant that the failure location could not be predicted in advance.

3.2 Instrumentation

The unreinforced Girder 1 was to be tested first with a minimum of instrumentation. Vertical displacements were measured only in the middle third using five displacement transducers. This caused problems as will be discussed later.

Girder 2 was reinforced with CFRP nominally 14mm thick. It consisted of 3 layers of Ultra High Modulus CFRP plates each 4.7mm thick. There were two sets of plates, each 200mm wide, located on the tension flange. There was also a thin layer of GRP between the cast iron and the CFRP to insulate the CFRP from the metal. All plates were bonded together and to the CFRP using epoxy adhesive. The adhesive layer between the CFRP and the cast iron was nominally 2mm thick The girder was heavily instrumented; displacements were measured as before and strain gauges were located close to midspan (see Figure 3) and close to one end of the CFRP.

Figure 2. Girder in four-point bending rig (courtesy Doosan Babcock Limited).

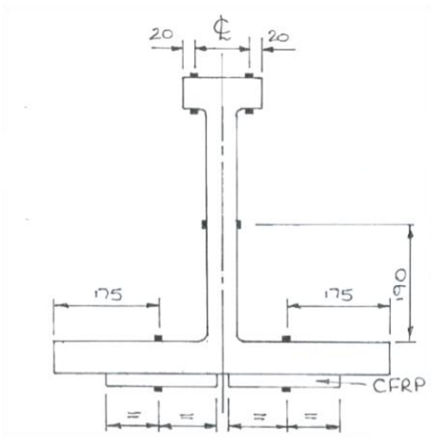

Figure 3. Strain gauge locations near mid-span, all 30mm gauge length

3.3 Test procedure

In the test rig each end of the specimen rested on a hydraulic jack via a semi-circular roller. At the third points the girder contacted the reaction frames via a 30mm plate and semi-circular roller. Chicken wire was wrapped around the girder to contain any fragments of the jack arch still attached to the girder. All instruments and the load cells measuring jack loads were connected to a data logger. Before applying any load a cover was placed over the test rig to contain any fragments of cast iron that might fly around at failure.

It was decided prior to testing that the specimen would not be bedded in by applying an initial loading cycle because the cross sections were distorted and there was concern about premature local damage. Equal loads were applied at each end and the load in each jack was increased at a constant rate of 1.0kN/s until failure occurred. All personnel were kept well away from the rig for safety and failure was recorded using video cameras.

4 TEST RESULTS

4.1 Failure modes and surfaces

The failure of the unreinforced girder occurred over a vertical section at one end of the constant bending region where the section modulus was smallest. The failure was instantaneous, running up from the tension flange. Using calculated section properties the maximum tensile stress was $104N/mm^2$. The failure surface, shown in Figure 4, was typical of old cast iron but also contained large slag inclusions in the web and tension flange. The variations in section thickness can also be seen.

Figure 4. Failure surface of the unreinforced girder, web left, flange right. Note the inclusions.

The reinforced girder behaved differently. When the jack load reached 327kN there was a sharp noise accompanied by changes in the strain readings close to midspan but complete failure did not occur. As load was increased further noises occurred. Complete, violent, failure finally occurred, the girder breaking into two large and several smaller fragments. One large piece, weighing about 1.5 tonnes, jumped off the test rig. Examination after the test showed that the initial sharp noise was caused by the outer 4.7mm thick layer of CFRP debonding from the middle layer and rupturing at one end of the constant moment length. The subsequent noises were caused by localised debonding until at total failure the remaining 9.4mm thickness of CFRP ruptured at the failure surface accompanied by debonding of the CFRP over half the length of the girder. The failure surface ran diagonally up the girder from the tension flange, starting about 200mm outside the constant moment length and ending up just inside, as shown in Figure 5 (left). The adhesive layer at the failure surface was approximately 20mm thick and the flange thickness considerably reduced. There was also a large slag inclusion in the flange. Consultation with TGP revealed that there had been localised erosion over a short length of the cast iron from the acidic exhaust gases from steam locomotives passing under the bridge and it had been necessary to increase the adhesive thickness over that length.

Figure 5. Failure surface of the reinforced girder, the flange (right) shows the very thick adhesive layer.

4.2 Failure Loads

Girder 1 sustained a maximum load of 674.6kN (337.3kN in each jack) giving a maximum bending moment of 954.6kNm. Girder 2 carried 970.6kN (485.3kN in each jack), a maximum bending moment of 1373.4kNm. The self-weight of the girders has been ignored in analysing the results. It represented a small increase (4.2% for the reinforced girder) in load carrying capacity. The CFRP strengthening increased the failure load by 43.9%, a considerable benefit. However, it is worth pointing out that this is based on single reinforced and unreinforced specimens and cast iron is a very variable material.

4.3 Displacements

When displacement transducer readings were plotted against applied load a limitation of the test rig became apparent. The measured deflections were a combination of overall bending, bedding-in of the distorted flanges and the displacements of the test rig. Careful analysis enabled the overall deflections at higher loads in the constant moment length to be separated out and typical flexural displacement plots for the reinforced girder are shown in Figure 6. Load-maximum flexural displacement plots are shown in Figure 7. Using the slopes of the graphs in Figure 7 as measures of stiffness, the reinforced girder was 53.5% stiffer. The maximum flexural displacement of girder 2 was 8.3mm in the central third which extrapolates (theoretically) to 70.4mm over the full span.

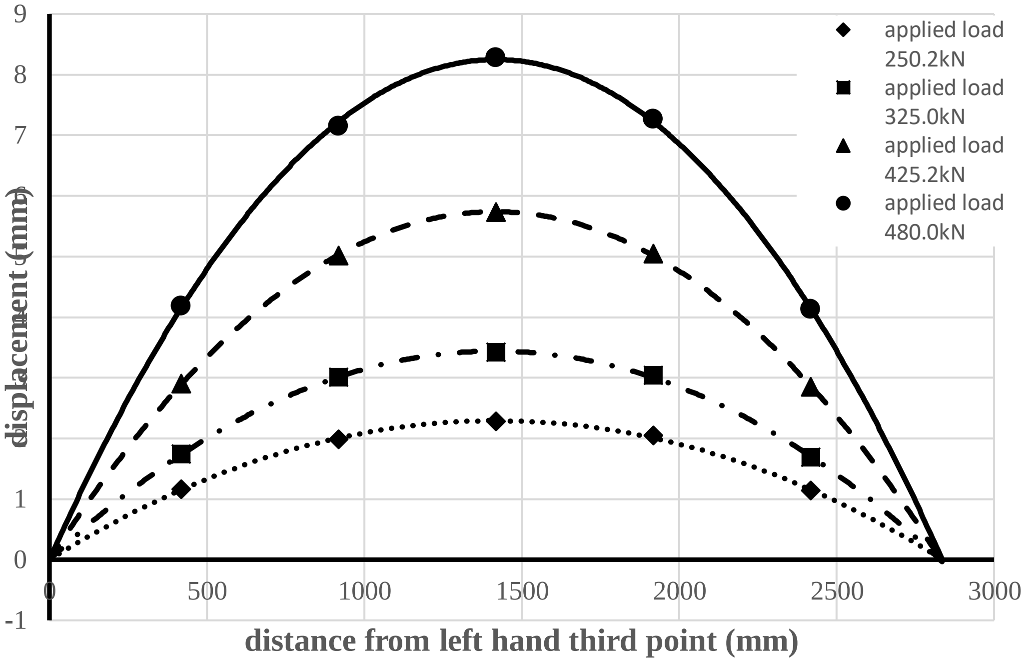

Figure 6: Flexural displacements, girder 2.

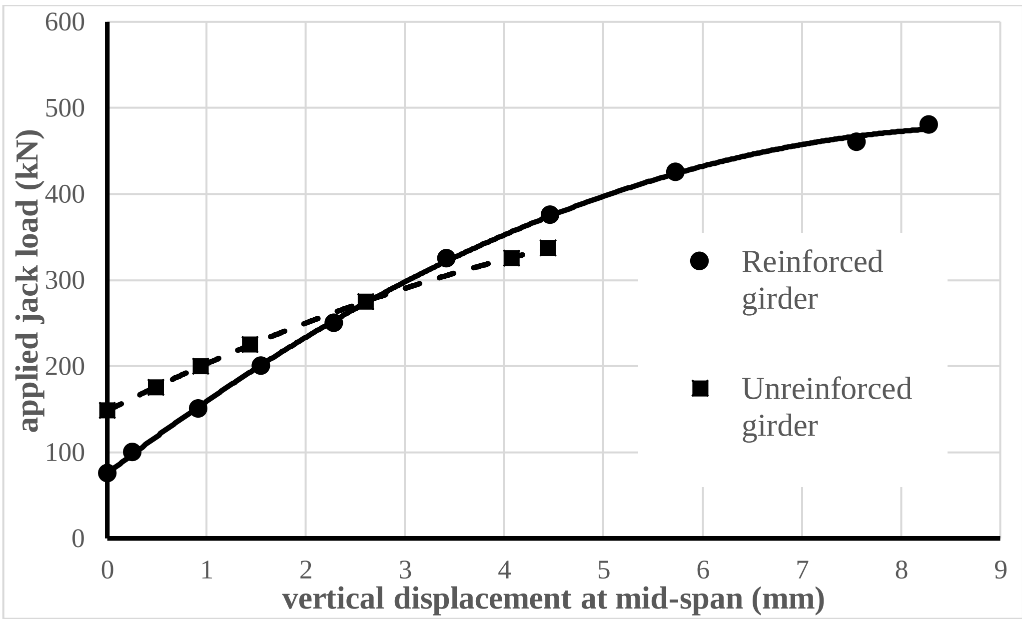

Figure 7: Maximum flexural displacements in both girders

4.4 Strains Close to Midspan

Figure 8 presents plots of the individual strain gauge readings close to midspan. As expected most of the cast iron was in compression during bending whereas the CFRP was in tension. The 'blips' in the curves are most likely localised debonding of parts of the carbon fibre. The major events coincided with failure of the outer plate of the CFRP. It can be seen that one plate of the pair failed at a lower load (gauges CFRP13 and CFRP14).

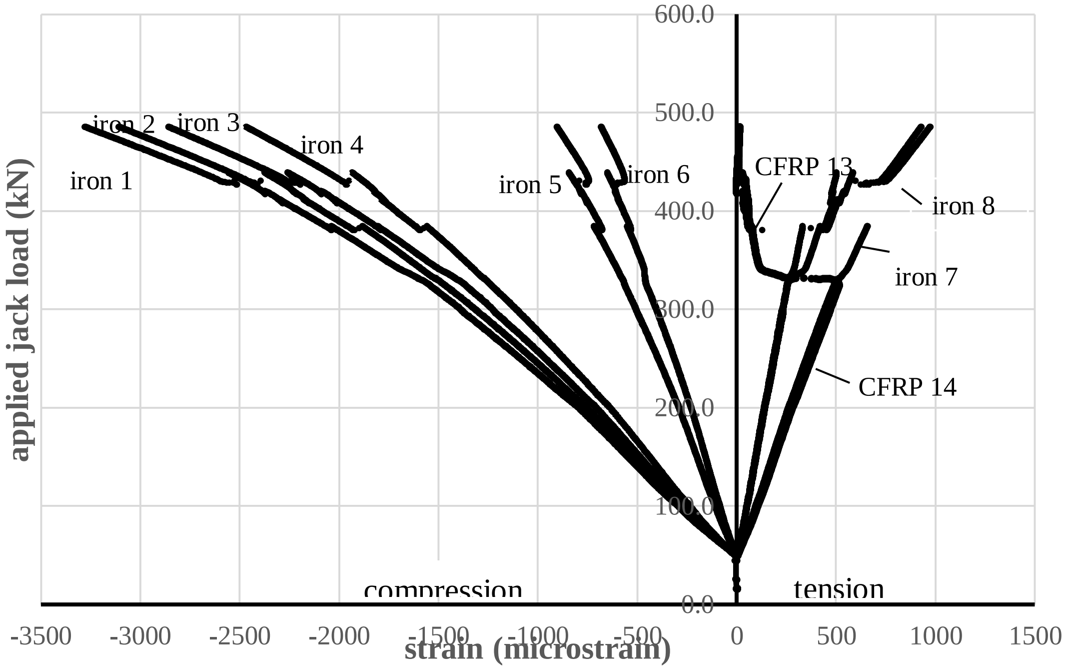

Figure 8: Strains near midspan, girder 2

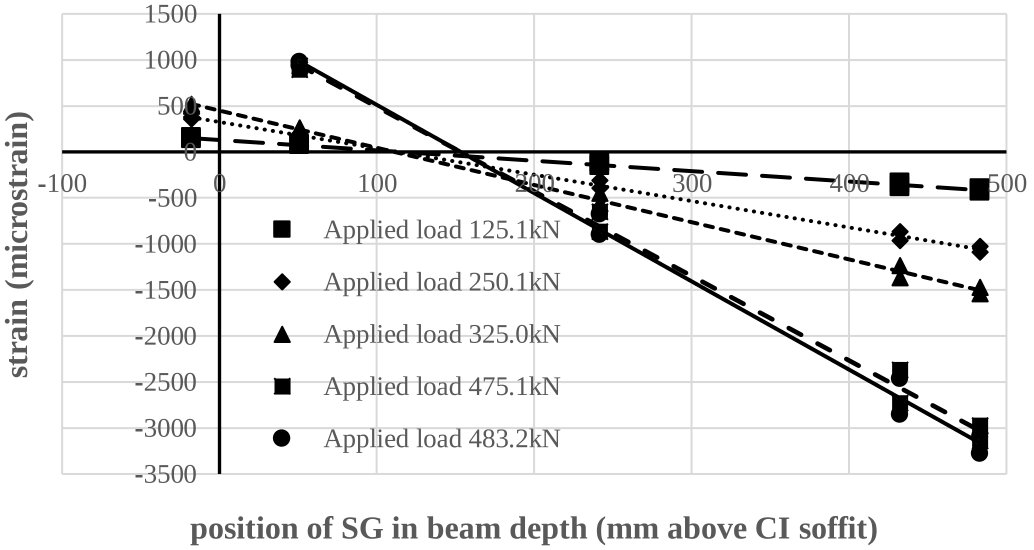

Figure 9: Strain distributions across depth of girder 2

Figure 9 shows strain distributions across the depth of the girder close to midspan. It can be seen that the distribution of strain was linear until initial failure of the carbon fibre and that the neutral axis hardly moved as load was increased. After failure of the outer plates of carbon fibre the neutral axis moved higher into the cast iron but then remained in the same position as the load increased. It is only speculation but it is possible that the strain distribution, as well as remaining linear across the depth of the cast iron, remained linear across the full depth of the remaining layers of carbon fibre. Extrapolating the strain distribution to the location of the outside fibres of the remaining carbon fibre gives a value of 1584 microstrain in the CFRP at the maximum load carried. The quoted failure strain of CFRP is between 1500 and 1900 microstrain.

4.5 Strains Near to the Ends of the CFRP Plates

The strain gauges near the ends of the CFRP did not provide any useful information.

4.6 Tensile Tests on the Cast Iron

Tensile specimens were machined from a fragment of the cast iron. The tests gave an average UTS of 143.8N/mm^2, higher than the calculated value of 104N/mm^2 at failure of girder 1, demonstrating the deleterious effect of the slag inclusions. The average measured elastic modulus was 71.0kN/mm^2 which compares well with the value of 73.4kN/mm^2 obtained by back calculation from the flexural test readings.

5 CONCLUSIONS

The testing of the cast iron girders was very successful providing evidence and reassurance at full scale of the efficacy of CFRP strengthening and stiffening. The reinforced girder was 43.9% stronger and 53.5% stiffer, similar to TGPs design predictions.

The CFRP was applied 12 years before the bridge was demolished and the tests have confirmed that it was working as intended. This gives confidence in the long-term efficacy of the technique since any problems would be expected in the first years after application of the CFRP.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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