Full scale cast iron girders reinforced with CFRP - flexural testing

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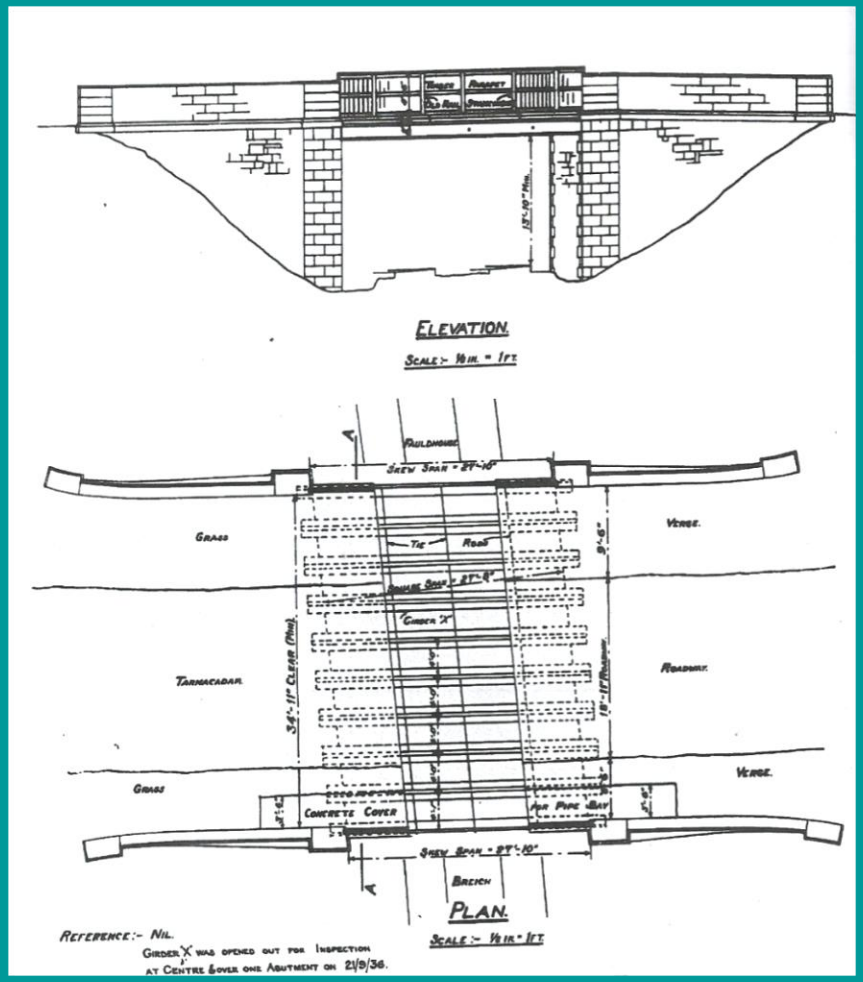
Breich Bridge, layout – built 1869



- Line between Glasgow and Edinburgh, Scotland
- Cast iron girders 9m long, 8.5m clear span. Concrete jack arches between
- Reinforced with CFRP in 2004
- Demolished due to electrification
- 2no. Girders removed almost intact

London Midland and Scottish Railway drawing from 1933

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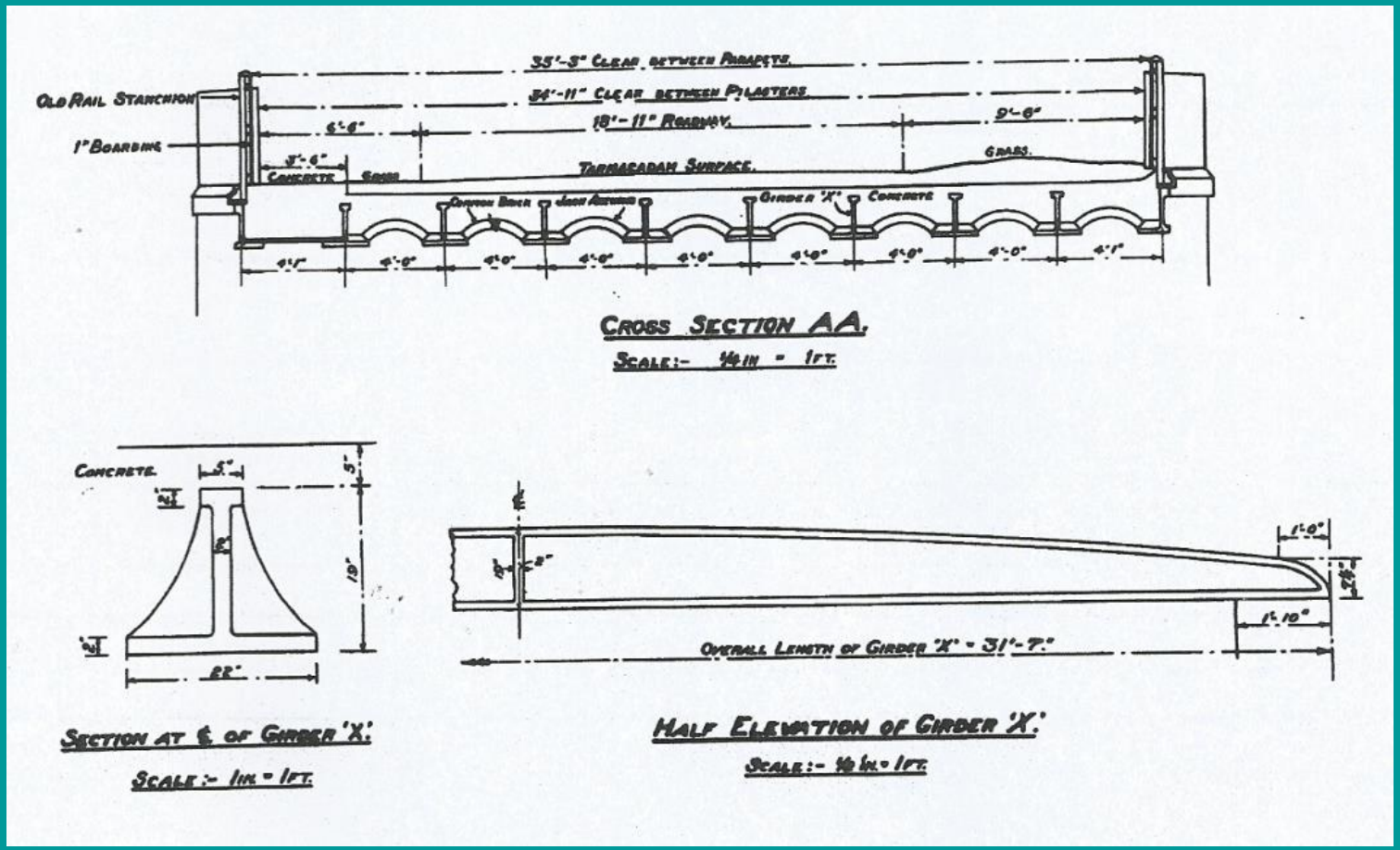
Breich Bridge - details



London Midland and Scottish Railway drawing from 1933

Details of the girders

Cast iron girders in the laboratory

Left hand girder – CFRP damaged, cut across to be ineffective.
Note remains of jack arch

Right hand girder – CFRP in good condition.
CFRP consisted of parallel plates, 200mm wide. Each plate had three 4.7mm thick prepreg UHM layers. All bonded with epoxy.

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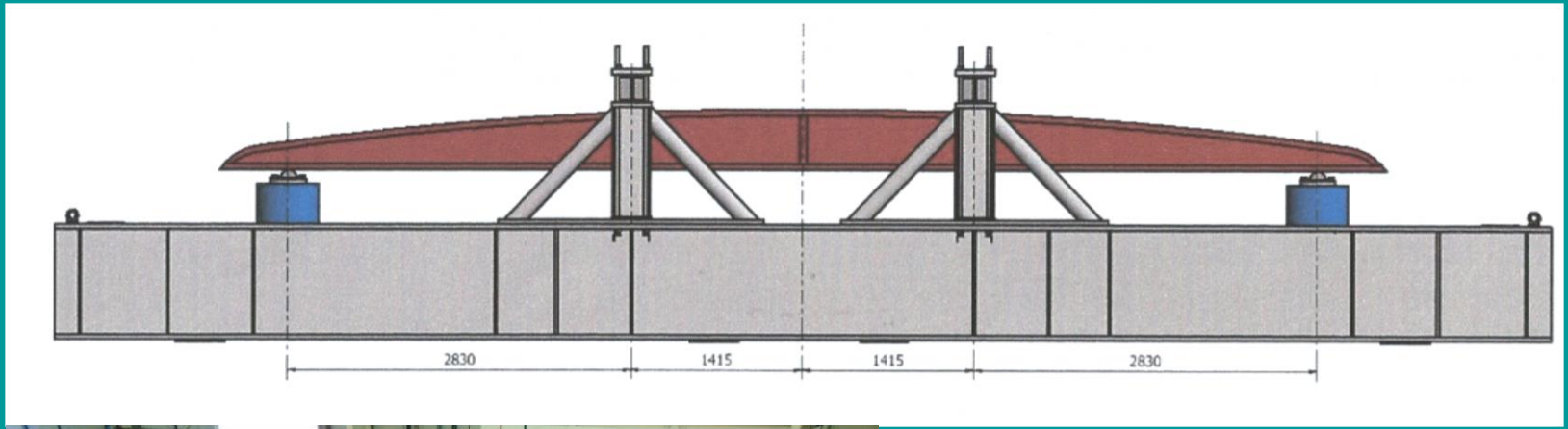
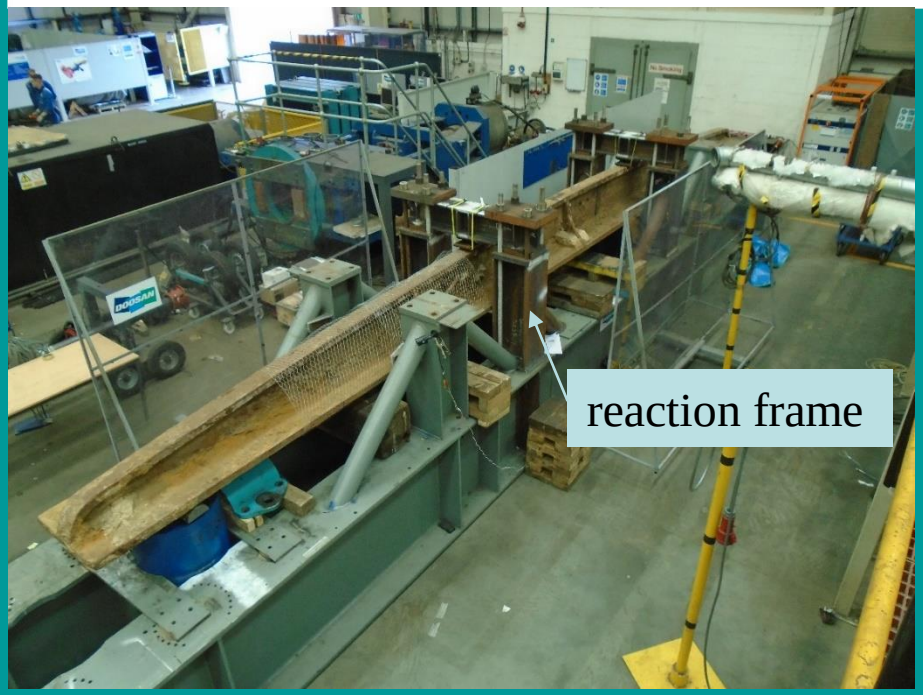
Schematic of test rig and photo of girder in the rig





Test rig applied load through jacks at each end. Loads reacted at third points.
Set-up not ideal, reaction frames deflected under load and displacement measurement difficult

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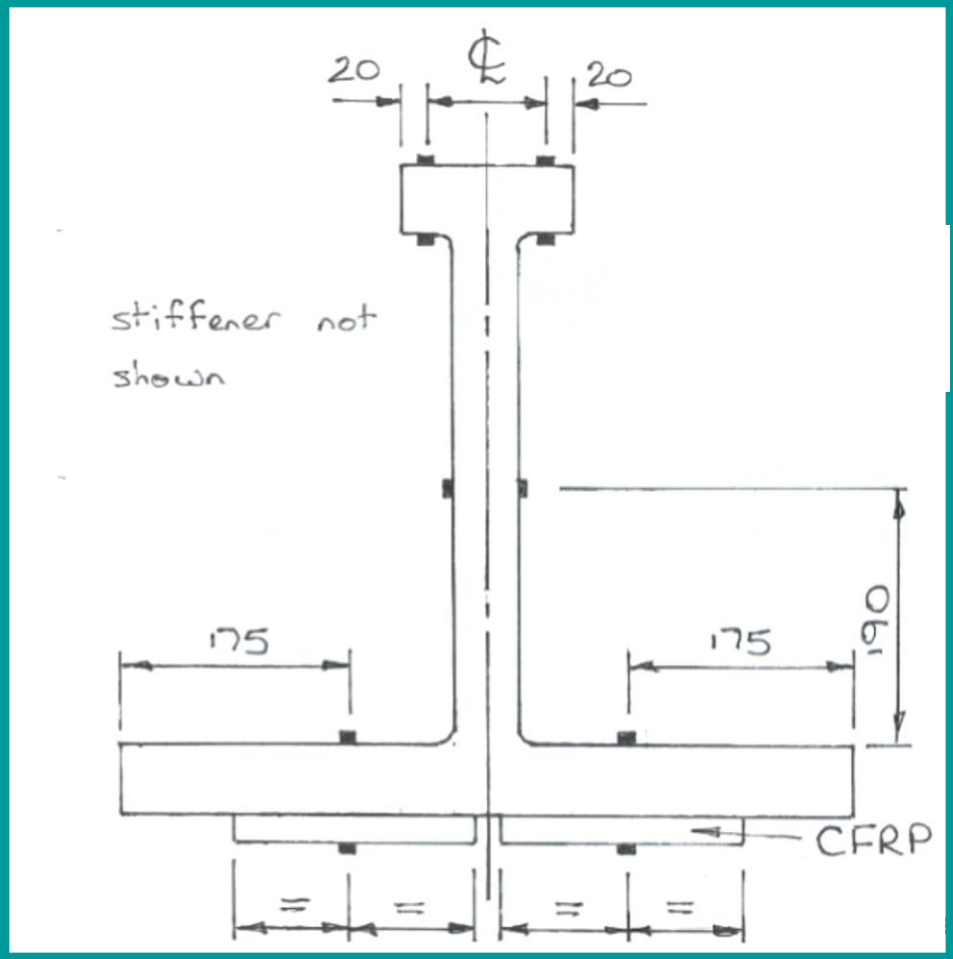
Strain gauge locations near midspan



All gauges 30mm gauge length
Located just to left of centreline to avoid stiffener

Failure of girder 1, unreinforced

- Unreinforced girder failed at end of constant moment length
- Typical failure surfaces for old cast iron

- Note the large slag inclusions in both web and flange
- Failure was instantaneous, running up from the tension flange
- Failure load 674.6kN, failure stress 104N/mm^2

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Failure of girder 2, reinforced

Failure was catastrophic, this fragment weighing about 1.5 tonnes jumped off the test rig. Testing cast iron is dangerous

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Failure of girder 2, reinforced

- Failure occurred just outside the constant moment length, combination of high BM and SF. Hence the inclined failure surface
- Texture of the failure surface is typical
- There was warning of failure, noises from localised debonding of CFRP

Failure of girder 2, reinforced

Outer 4.7mm thick layer of CFRP debonded and broke at about 680kN load

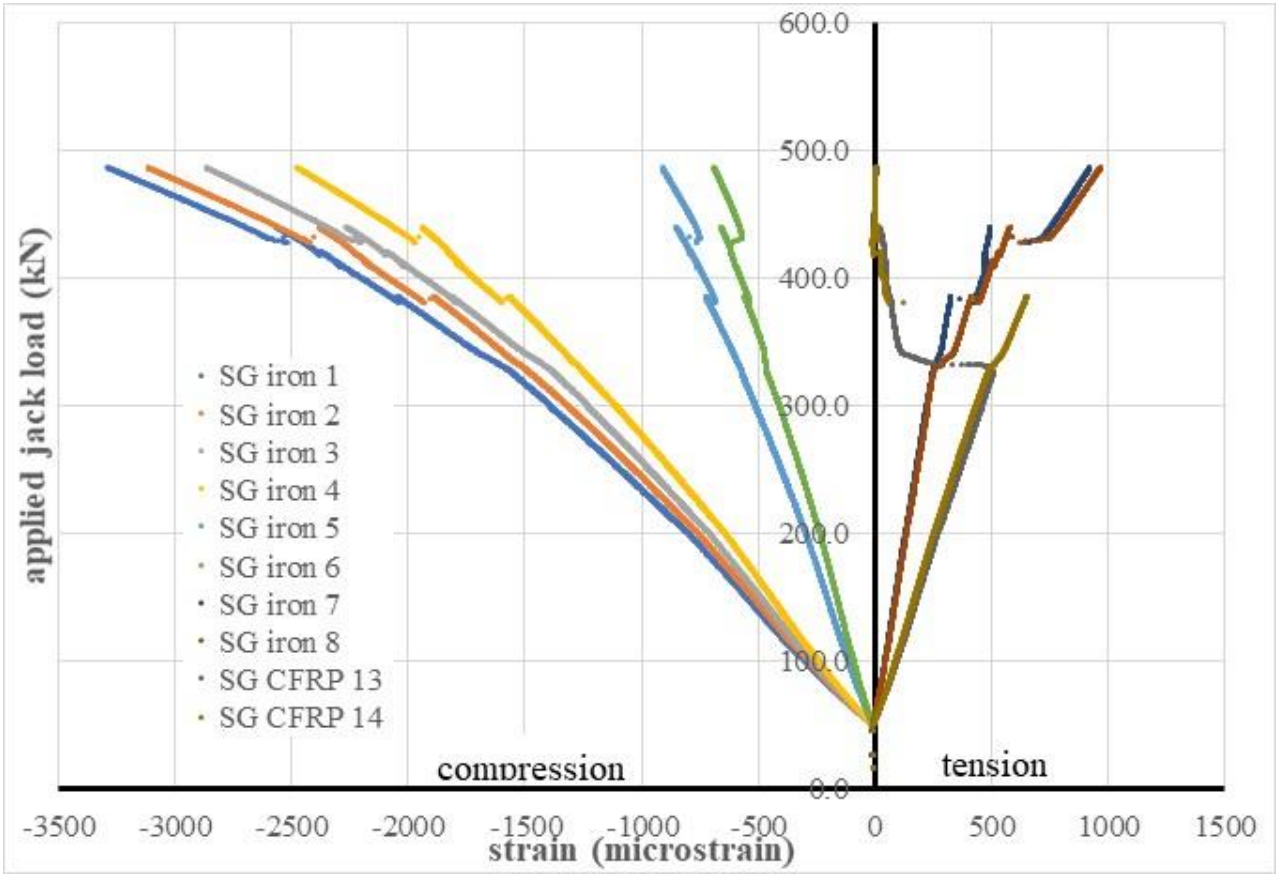
- Complete failure occurred at 970.6kN
- CFRP ruptured and the cast iron broke in two
- Note the GFRP layer

Failure of girder 2, reinforced

- What was unexpected was the 20mm thick adhesive on the failed flange.
- Note also the slag inclusion and the reduced flange thickness

- The explanation came from Tony Gee and Partners the designers of the strengthening scheme.
- The steam from early locomotives was acidic and eroded the metal locally

Selected results – strain gauge readings



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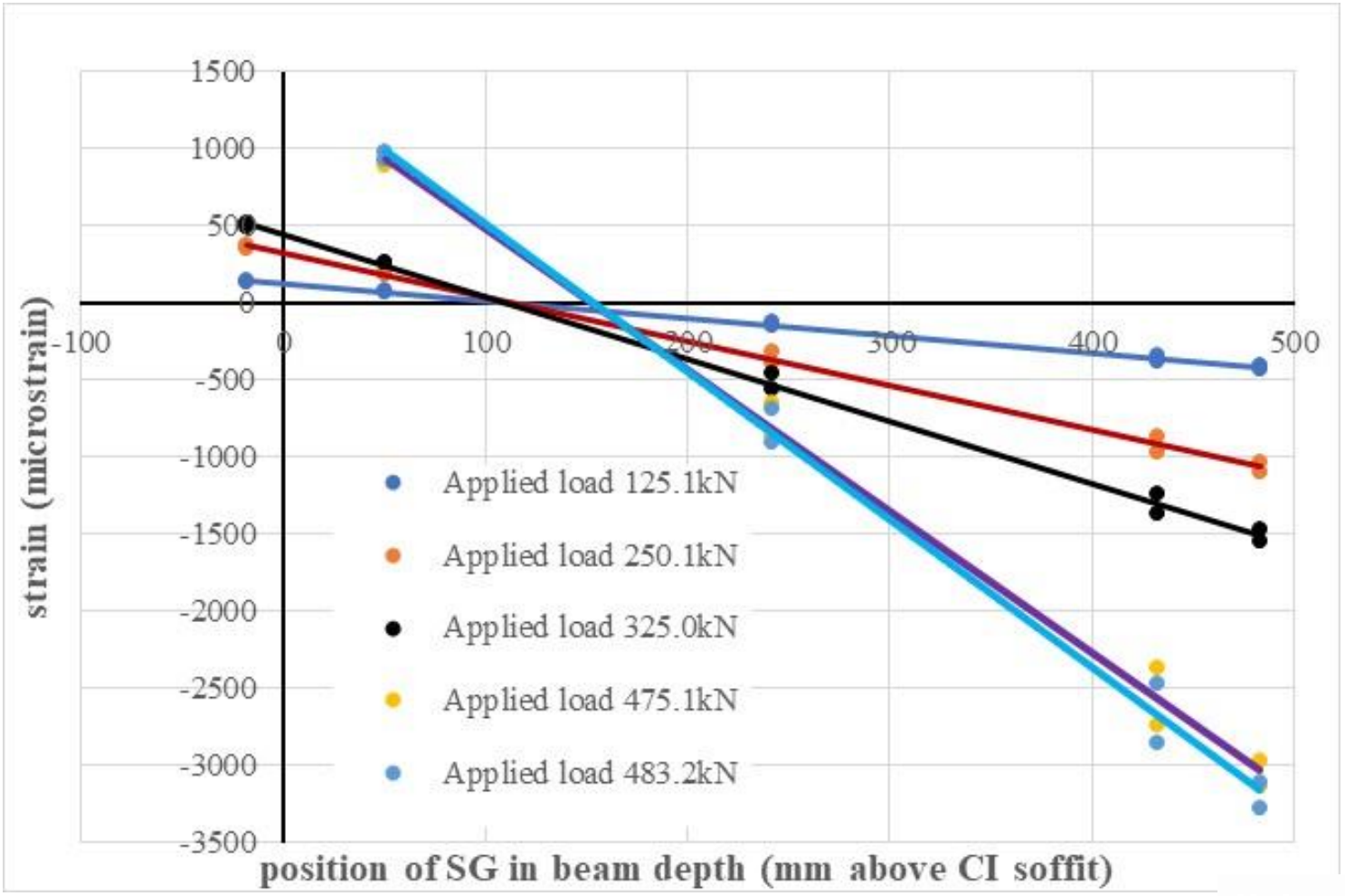
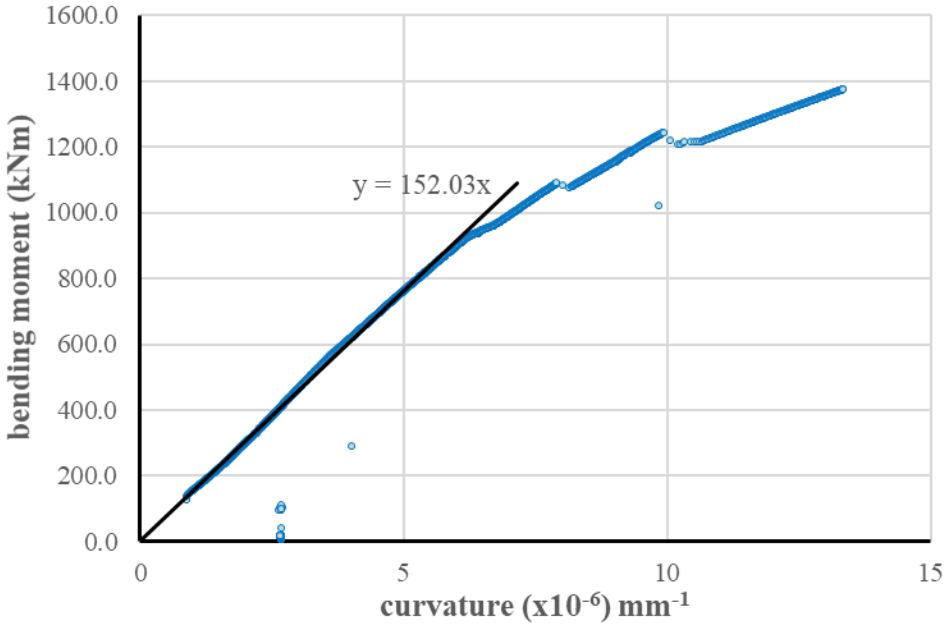
Selected results – strains across depth of CFRP and CI



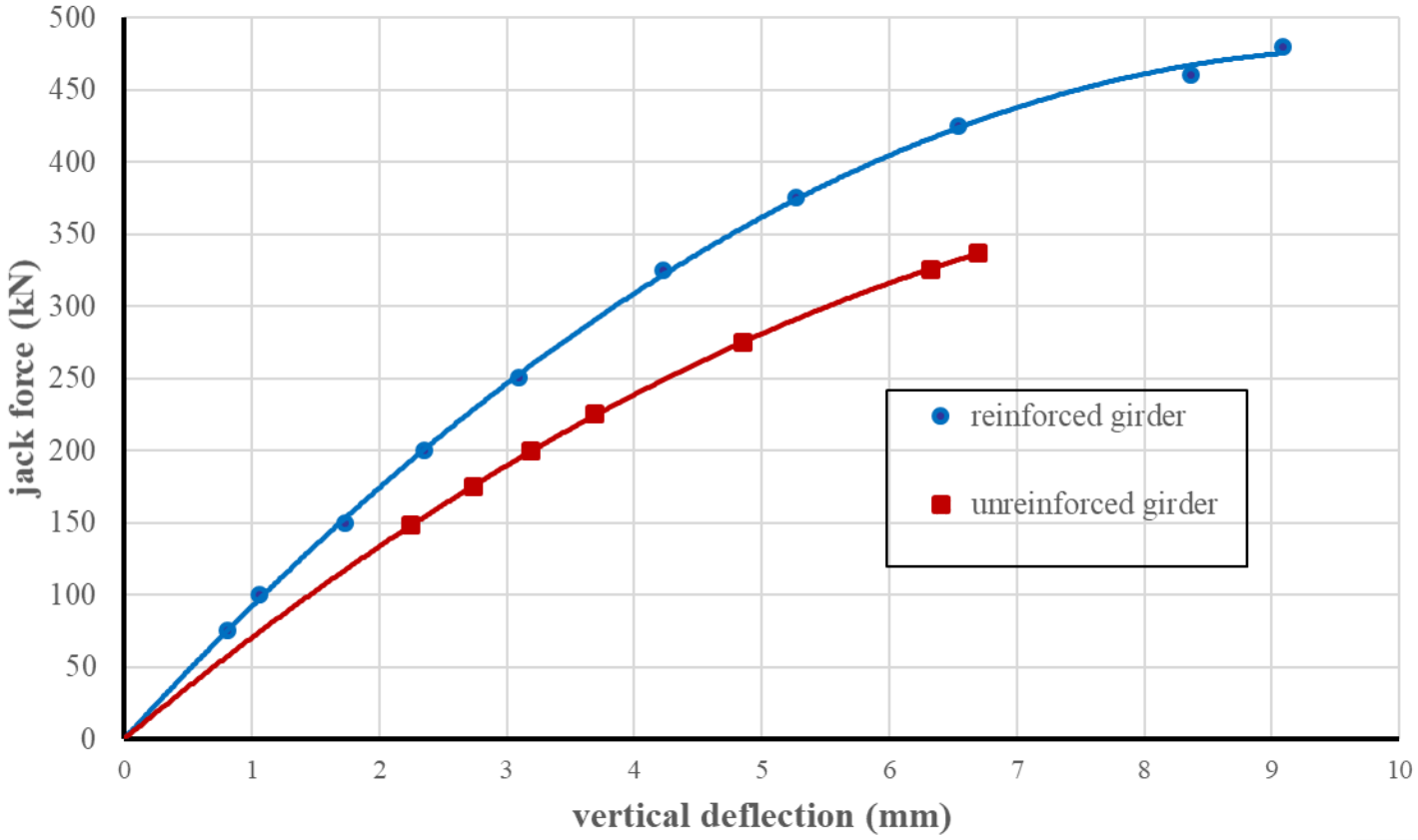
Moment-curvature relationship, reinforced girder



- Moment-curvature relationship for girder 2, calculated from strain gauge readings
- Table shows how stiffness reduced with increasing load
- The equivalent I values agree closely with calculated values

Phase	Moment Range (kNm)	Slope ($kNmm^2x10^9$)	Equivalent 'I' value (mm^4)
1	140-934	152.0	$2.14x10^9$
2	954-1081	108.7	$1.53x10^9$
3	1076-1237	95.3	$1.34x10^9$
4	1215-1369	58.7	$0.83x10^9$

Selected results – maximum flexural displacements in middle third of girders



Conclusions

1. Testing at full scale demonstrated the effectiveness of CFRP strengthening of metallic structures
2. The girder reinforced with CFRP carried 43.9% more load than the unreinforced girder
3. Comparing effective ‘I’ values, the reinforced girder was 30.7% stiffer than the unreinforced girder
4. The CFRP strengthening was applied 12 years before the bridge was demolished and was still working as intended. This gives some confidence in the long term effectiveness of the technique
5. One note of caution, the results were based on single tests and cast iron is a notoriously variable material! I’m told that other girders were removed intact but Network Rail haven’t taken my hints!

Acknowledgements

Despite my previous dig I would like to thank Network Rail for funding this work.
Doosan Babcock Ltd in Renfrew were responsible for the testing and did an excellent job. Craig Millar in particular ran the tests in a very professional manner and has been very helpful throughout. Many of the photographs in this report were provided by him.
I would also thank Tony Gee and Partners for their input concerning the strengthening.