

The strengthening of a steel bridge with prestressed CFRP strips

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Abstract. The use of CFRP (carbon fibre reinforced polymer) strips in steel strengthening works has gone through a big development during the past 15 years. However, only in a few studies the effect of prestressing on the behaviour of steel beams strengthened with the CFRP strips has been examined. The paper briefly describes the research on the new CFRP strips prestressing system with special steel anchorages and its first on-site application for a steel bridge strengthening. The bridge proof tests before and after strengthening have been carried out. The results of testing proved the strengthening efficiency, however the final effect was moderate. As a result of strengthening the following effects has been gained: max. 18.3 % reduction of mid-span deflection and max. 13.9 % reduction of stresses in steel beams. The CFRP strengthening slightly improved the overall dynamic performance of the bridge span as well. The tests results showed moderate strengthening effects, mainly due to beams geometrical constraints not allowing to apply more than one 60 x 14 mm strip per beam. Regardless the moderate efficiency of strengthening, the research results clearly revealed that the new strengthening technology could be efficiently applied for steel bridges.

1. Introduction

The CFRP materials, as viable alternative to structural strengthening, offer several advantages such as high strength to weight ratio, light weight, ease of transport and installation, excellent fatigue characteristics and non-corrosiveness (durability). A few different approaches have been investigated to assess the effectiveness of the CFRP materials for strengthening of steel structures. Since the beginning of the new millennium, more than one hundred research papers on strengthening of steel structures with the CFRP materials have been published in scientific journals and conference proceedings. The most important research findings were reviewed and summarized in the following state-of-the-art reports [1-4]. These reviews showed that the load-carrying capacity of the CFRP-strengthened beam can be increased regarding stiffness and strength. In the case of the degraded beams, it was found out that the load-carrying capacity could be partly or fully restored by the strengthening system. Field applications have also been carried out on bridge girders, see [5-7] for example, which resulted in the stresses in the original beams being reduced. On the basis of these studies, it was concluded that using bonded CFRP plates as a strengthening system can be effective.

By prestressing the CFRP plate, which combines benefits of passive bonded plate with the advantages due to external prestressing, the ultra-high tensile strength of carbon fibres can be utilized and much higher effectiveness of the strengthening technique is achieved. A greater CFRP's tensile capacity is employed and it contributes to the load carrying capacity of the strengthened steel structure



under both service and ultimate conditions. However, only in a few studies the effect of prestressing on the behaviour of steel beams strengthened with the CFRP plates has been examined [8-13]. The anchor zones in plate end locations has been the main problem of steel beam strengthening with the CFRP prestressed plates. Without mechanical anchorages, the peeling failures at the plate ends were observed. Premature debonding of the CFRP plates is one of the most common failure modes, and it could occur before the stress in the CFRP material reaches its tensile strength. Nevertheless, more detailed investigations are needed to obtain a good understanding of the way the forces acting inside the strengthening system and the way different parameters of the CFRP plate affect the behaviour of the strengthened beam.

The main goal of the R&D study was to compare the flexural behaviour of steel beams strengthened with the CFRP plates. This research evaluated two strengthening schemes, namely: (1) adhesive bonded passive plates and (2) adhesive-bonded active or prestressed plates, with different strengthening configurations and CFRP materials. The previous author's paper presents the results of an experimental investigation carried out on the behaviour of steel beams before and after strengthening using different CFRP systems [14]. In the scope of the R&D study the actual bridge proof tests before and after strengthening was also carried out. The results of bridge testing proved the strengthening efficiency, however the final effect was moderate. Nevertheless the presented case study revealed the effectiveness of the new prestressing system, which seems to be reliable for steel bridge applications. The strengthening technology, its first application on a steel bridge and discussion of bridge proof testing results have been the main subject of the paper.

2. Novel CFRP Prestressing Technique

The new system called *Neoxe* consists of two main elements: special steel anchorages mounted on both ends of a single CFRP strip and a relevant tensioning device. There are two kinds of anchorages: an active anchorage combined with a tensioning device and a passive one. The strip with a specific length is delivered on site as ready-to-install, i.e., with two prefabricated steel anchorages mounted on both strip ends. The anchorage is made of two thin steel plates welded together along the edges to create a pocket, in which the CFRP strip end is fixed and bonded with a special epoxy-based adhesive. It is followed by gripping both materials (steel plates and CFRP strip in-between) with small mechanical fasteners: rivets or high-strength bolts (Fig. 1).

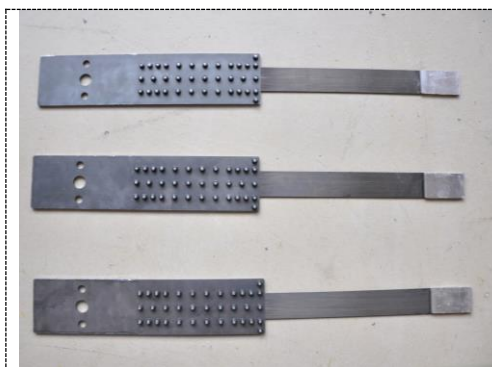


Figure 1. Steel anchorages

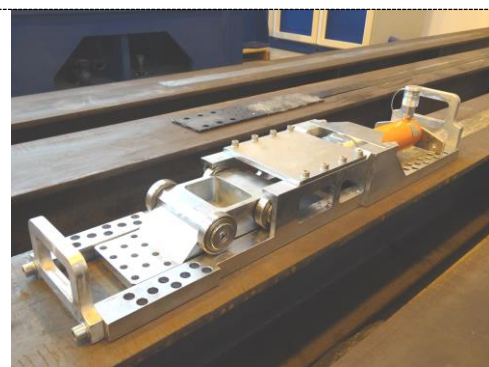


Figure 2. Tensioning device

However, it is often said, that galvanic corrosion may be occurred in a CFRP/steel system because of direct contact between steel and CFRP surfaces accompanied with an electrolyte like salted water. It was showed using a nonconductive fabric between two materials, an isolating epoxy layer on the steel surface, and a moisture buffer decreased significantly the rate of corrosion. Meanwhile, epoxy adhesive usually play the role of insulator [15].

The tensioning device is the second key element of the strengthening system. The tensioning device consists of three separately installed components: guide rails, carriage (bolted to the active

anchorage) and hydraulic jack with resisting block (Fig. 2). The hydraulic jack is driven by a manual pump, and it can generate a subsequent tensioning force to stretch the CFRP strip. Owing to division of the device structure into three small and lightweight parts (the heaviest element weighs 37 kg), its manual application on-site is very fast and easy without using the heavy equipment.

The high-strength UHS 614 strips with a cross-section of 60×1.4 mm, with the ultimate tensile strength of 3200 MPa, a modulus of elasticity of 160 GPa and the strain at failure of approximately 2% are typically used in the NPS-II for strengthening. To complement the system, an epoxy-based adhesive is used for the final bonding of the strip between anchorages to the concrete substrate. The development and experimental investigation of a novel anchor and tensioning system for the flexural strengthening of steel as well as RC elements with prestressed CFRP strips has been presented in [16].

3. Bridge description

The bridge is situated along the local road over the small river. This is a simply-supported structure with the span length of 11.92 m and the total width of the deck of 7.41 m (Fig.3). The superstructure consists of five INP 500 rolled I-beams spaced at 1.40 m and laterally braced with C300 rolled channel sections spaced at 3.75 m along the bridge. This steel grid is covered with the temporary timber deck with no sidewalks, which state of repair was quite bad. The bridge span is supported by two concrete abutments founded directly on the ground. Because of deteriorated timber deck the carrying capacity of the bridge was posted to 15 metric tonnes and thus the bridge became the cumbersome bottleneck on the local road.



Figure 3. The steel bridge before strengthening.

These bridge constraints and the growing traffic on the local road caused the local road administration had made a decision to strengthen the bridge along with timber deck replacement into the new RC deck slab having wider roadway and sidewalks. The main goals of the modernization were as follows: to replace the timber deck into a durable RC slab, to increase the bridge carrying capacity up to 40 tonnes, to widen the roadway up to 6.0 m and to create at least one sidewalk. As the steel grid structure and the concrete abutments were in good condition it was decided to re-use them in the bridge modernization.

4. Bridge strengthening and modernization

Due to financial constraints the local administration divided the modernization works into two phases. In the first phase the steel grid was strengthened to carry the new RC slab deck and the increased traffic load, ultimately for 40 tonnes vehicles. The deck replacement & widening along with the approach road reconstruction were planned to be done in the second phase, one year later. However, the first phase' works enabled to increase the bridge carrying capacity up to 30 tonnes immediately after steel strengthening execution, complemented with the partial replacement of the most deteriorated timber elements.

The INP 500 rolled I-beams were strengthened with the *Neoxe* system by means of the prestressed UHS 614 *neoxeplate* CFRP strips with the average material parameters as stated above (p.2). On each

beam one strip was installed, glued and anchored after prestressing. The prestressing force determined in the detailed calculation taking into account two-phase strengthening was in the range of 137÷147 kN (depending on beam location), which capitalized the ultimate strength of CFRP in the range of 50÷55% respectively. The main stages of the strengthening procedure on-site were as follows: steel and CFRP surface preparation, adhesive application, mounting the passive anchorage on steel beam (Fig.4), mounting the tensioning device on the opposite end of the beam (Fig.5), trial strip prestressing, mounting the active anchorage on steel beam, final strip prestressing, strip bonding to steel substrate along with removing the adhesive excess. The steel anchorages were mounted on the steel beams by means of the 10.9 class HSFG bolts. No traffic limitation was required during the strengthening works.



Figure 4. Passive anchorage mounted on the steel beam



Figure 5. Mounting the tensioning device

In the second phase of bridge modernization one additional steel beam will be added to facilitate the bridge deck widening and the new RC deck slab will be executed replacing the timber deck. Before the new concrete slab is cast, the shear studs will be mounted on beams' top flanges to ensure the full composite action of the new steel/concrete beams after rehabilitation. The achievement of the composite action is as much efficient for bridge strengthening as the CFRP prestressing, implemented in the first phase.

5. Evaluation of the strengthening efficiency

5.1. Tests description

To assess the efficiency of the bridge strengthening, two proof tests were carried out during the first phase of the modernization works: before and after steel strengthening. In both tests exact the same load was placed on the bridge to compare the relevant strains and displacements and to evaluate the superstructure behaviour. Two trucks with the mass of 32 metric tonnes each were used for static tests whereas one of them was further applied for dynamic tests as well. The total proof load was limited due to timber deck capacity and its bad state-of-repair. Therefore only 40 – 45 % of the ultimate strength of steel beams was capitalized during static tests.

In both tests the vertical displacements in the mid-span of all beams were measured by means of the linear variable displacement transducers (LVDTs) with 100 mm base (points D1 – D5). Moreover, the 10 mm foil strain gauges were applied for strain measurement both in steel beams as well as in the CFRP strips. The steel strains were detected in the top and bottom flanges of each beam in the mid-span (points S1-S5) (Fig.6). The CFRP strains were measured in 8 points along the central beam's strip (C3/1-C3/7) (Fig.7). All gauges were connected via the set of QuantumX MX840A amplifier modules to the computer with Catman Easy data acquisition software. The signal of the selected LVDTs and strain gauges was also applied to determine the dynamic characteristics of the bridge span before and after strengthening.

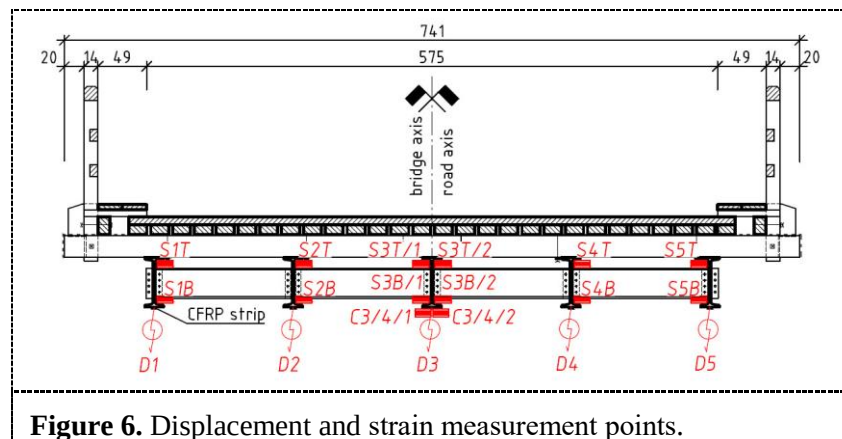


Figure 6. Displacement and strain measurement points.

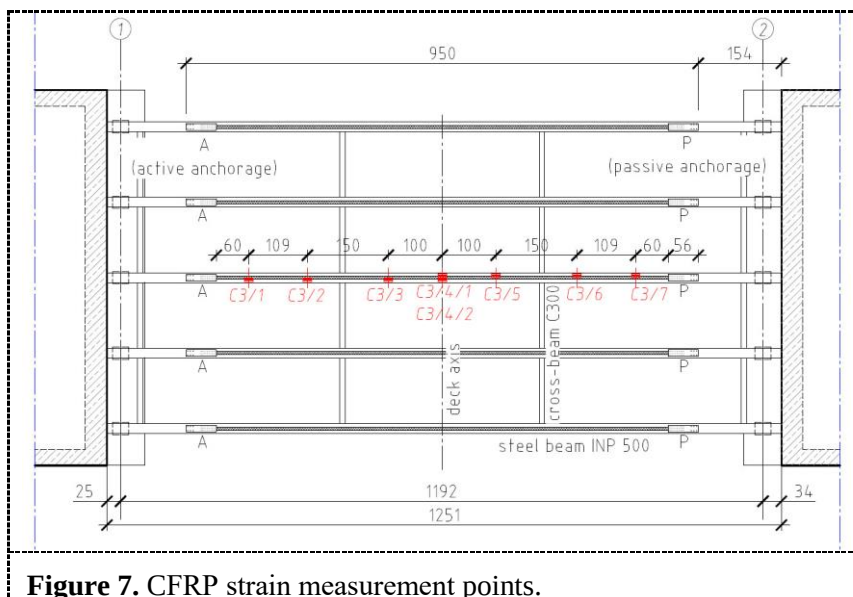


Figure 7. CFRP strain measurement points.

5.2. Static tests results

In Tables 1, 2 and 3 the both tests results (i.e. before and after strengthening) are collected to be directly compared in order to assess the strengthening efficiency. The strengthening efficiency in this particular case is defined as the percentage of the reduction of the mid-span deflection as well as the decrease of steel strains (stresses) in steel beams. To give an idea of beam's carrying capacity capitalization the experimentally obtained strain values are converted into stresses with the assumption of modulus of elasticity of 205 GPa for steel and of 160 GPa for CFRP respectively. The stresses in CFRP strips enabled to assess the utilisation of composite material under bridge full loading, having in mind the initial stresses induced by prestressing.

Table 1. Beam's mid-span deflection before and after strengthening.

Beam	Measurement point	Deflection before (mm)	Deflection after (mm)	Reduction (%)
1	D-1	18.05	16.64	7.8
2	D-2	23.69	21.92	7.5
3	D-3	30.60	24.99	18.3
4	D-4	23.40	20.90	10.7
5	D-5	18.37	16.79	8.6

The stress reduction in steel beams due to strengthening was moderate: from 6.2 to 13.9 % in the bottom flanges and from 1.1 to 8.9 % in the top flanges depending on the beam location (Table 2). The reduction in the most loaded central beam was almost equal for the both flanges, but in the adjacent, outer beams higher reduction in the bottom flanges was obtained. However, there is a scatter of strengthening effects despite the symmetry of the span structure as well as loading. It is mainly due to uneven contribution of timber deck in load carrying capacity of the steel beams, influencing the lateral load distribution. The small differences in the prestressing forces in particular beams could also influence the stress distribution after strengthening.

Table 2. Stresses in steel beams before and after strengthening.

Beam	Measurement point	Stress before (MPa)	Stress after (MPa)	Reduction (%)
1	S1T	-69.7	-65.8	3.0
1	S1B	56.0	52.5	6.2
2	S2T	-92.7	-91.6	1.1
2	S2B	88.6	83.4	7.9
3	S3T/1	-107.4	-98.4	8.4
3	S3B/1	104.9	96.6	7.6
3	S3T/2	-110.1	-100.2	8.9
3	S3B/2	102.9	93.7	9.0
4	S4T	-83.2	-77.9	6.4
4	S4B	91.2	78.5	13.9
5	S5T	-69.3	-66.0	4.7
5	S5B	67.9	63.1	6.9

The analysis of the composite strains clearly shows, that the CFRP strips contributed successfully in beam's load carrying capacity (Table 3). However, the composite strains induced by bridge loading constituted only maximum 5.17 % of the total strains of CFRP strips. The strains due to the initial prestressing (10.19 ‰) are always decisive for the capitalization of the ultimate strength of the CFRP strips. It was about 50% in this strengthening case. The strain distribution along the CFRP strip mounted on the most loaded central beam was decreasing from the mid-section towards strip ends. The strains induced in or close to steel anchorages were negligible what proved the reliability of the strengthening system in terms of fatigue. All test results confirmed the appropriate behaviour of the CFRP strengthened superstructure under loading.

Table 3. Composite strains and stresses along the CFRP strip in beam 3.

Measurement point	Strains before (‰)	Strains after (‰)	Total stresses (MPa)	Material use (%)
C3/1	10,19	0.369	1659.04	50.58
C3/2		0.472	1675.52	51.08
C3/3		0.532	1685.12	51.38
C3/4/1		0.552	1688.32	51.47
C3/4/2		0.555	1688.80	51.49
C3/5		0.514	1682.24	51.29
C3/6		0.389	1662.24	50.68
C3/7		0.278	1644.48	50.14

5.3. *Dynamic tests results*

The dynamic test of the bridge span before and after strengthening was carried out by means of one truck with the mass of 32 metric tonnes passing the bridge with two different velocities: 30 and 50 km/h. The dynamic response of the span was detected with LVDTs in the mid-span location for beams 3 and 4. Generally it can be said, that the CFRP strengthening slightly improved the overall dynamic performance of the bridge span. The first eigen frequencies increased in the range of 5.3 to 12.5 % after strengthening and simultaneously the dynamic factors were reduced by 15% in average. The strengthening enhanced also damping characteristics of the span increasing the logarithmic decrement by more than 20% in average. The measured dynamic characteristics had a slight scatter and did not clearly depend on the vehicle velocity and beam location.

5.4. *Analysis of results*

The main goals of a bridge strengthening are always at least to decrease deflections and/or to relieve a structure, which means to reduce the stresses in subsequent bridge elements, mostly main beams or girders. Taking into account these goals it can be said, that the bridge strengthening with CFRP prestressing let to achieve only moderate effects. The quantitative estimation of these effects are as follows: max. 18.3 % reduction of mid-span deflection and max. 13.9 % reduction of stresses in steel beams. Moreover, the CFRP strips were almost not affected by the proof load, because the only maximum 5.2% increase of composite strains was detected.

There are several reasons the strengthening efficiency is so moderate. First of all the proof load was considerably limited due to deteriorated and only partially repaired timber deck. Under the applied loading only about 40% of the load carrying capacity of the bridge was capitalized in terms of steel strength. The larger steel capitalization under service load, the higher strengthening efficiency. The efficiency limitation was caused by the fact that only one CFRP strip per beam might be applied due to its geometrical constraints. On the other side the higher prestressing force might jeopardize the local stability of the beam's top flange, not supported by a compositely acting deck slab. In more likely cases when beams are connected to the RC deck slab the prestressing could reach the allowable level, i.e. about 70% of the ultimate strength of the CFRP strip. In our case however the strengthening CFRP strips take part of the self-weight of the future RC slab, thus increasing the utilization (and efficiency) of composite material.

6. **Conclusions**

The first phase of the steel bridge modernization including strengthening, redecking and widening has been presented in the paper. In this phase the strengthening of steel beams with the prestressed CFRP strips was the main intervention. Two bridge proof tests: before and after strengthening, enabled to check and prove the strengthening efficiency. The strengthening was applied to typical rolled steel beams covered with the timber deck not structurally connected with beams. The comparison of two tests results showed moderate strengthening effects, mainly due to beam's geometrical constraints not allowing to apply more than one strip per beam. The limited proof load used in proof tests also affected the final results and thus the obtained efficiency. However, the CFRP strips contributed successfully in load carrying capacity of the bridge. The moderate quantitative results of the strengthening will be considerably enhanced in the second phase of bridge modernization.

Regardless the moderate efficiency of strengthening, the research clearly revealed that the new strengthening technology using the prestressed CFRP strips could be efficiently applied for steel beam bridges and enabled to strengthen them up to the required carrying capacity. The strengthening level depends on particular geometrical and technological constraints of the existing bridge and works to be undertaken for its modernization. The strengthening system can be quite quickly implemented on-site without traffic limitations and significant structural intervention. Moreover, due to long-lasting material used for strengthening the final effect seems to be much more durable than in case when another methods of steel bridge strengthening would be applied.

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References

- [1] Hollaway L C and Cadei J 2002 Progress in the technique of upgrading metallic structures with advanced polymer composites *Progress in Structural Engineering and Materials* **4** pp 131–148
- [2] Shaat A, Schnersch D, Fam A and Rizkalla S 2004 Retrofit of steel structures using fiber-reinforced polymers (FRP): state-of-the-art *Proc. 83rd Annual Meeting of the TRB (Washington)* on CD pp 1-18
- [3] Zhao X L and Zhang L 2007 State of the art review on FRP strengthened steel structures *Engineering Structures* **29** pp 1808–1823
- [4] Teng J G, Yu T and Fernando D 2012 Strengthening of steel structures with fiber-reinforced polymer composites *Journal of Constructional Steel Research* **78** pp 131–143
- [5] Luke S 2001 The use of carbon fibre plates for the strengthening of two metallic bridges of an historic nature in the UK *Proc. Int. Conf. on FRP Composites in Civil Engineering (Hong Kong)* ed J G Teng (Amsterdam: Elsevier) pp 975-983
- [6] Wipf T J, Phares B M, Klaiber F W, Lee Y S, Al-Saidy A H, Abu-Hawash A and Monk C 2004 Use of CFRP plates in the strengthening of steel girder bridges *Proc. 2nd Int. Conf. on Bridge Maintenance, Safety and Management (Kyoto)* ed E Watanabe, D M Frangopol and T Utsunomiya (Boca Raton: CRC Press) pp 18- 22
- [7] Miller T C, Chajes T J, Mertz D R and Hastings J N 2001 Strengthening of a steel bridge girder using CFRP plates *Journal of Bridge Engineering* **6** pp. 514-522
- [8] Al-Emrani M and Kliger R 2006 Analysis of interfacial shear stresses in beams strengthened with bonded prestressed laminates *Composites Part B: Engineering* **37** pp 265–272
- [9] Benachour A, Benyoucef S, Tounsi A and Adda Bedia E A 2008 Interfacial stress analysis of steel beams reinforced with bonded prestressed FRP plate *Engineering Structures* **30** pp 3305–3315
- [10] Soudki K, Schumacher A and Motavalli M 2009 Flexural strengthening of a steel beam with prestressed strips-preliminary investigation *Proc. 9th Int. Symp. on Fiber Reinforced Polymer Reinforcement for Concrete Structures (Sydney)* ed D J Oehlers, M C Griffith and R Seracino (Adelaide: University of Adelaide) pp 1-4
- [11] Ghafoori E and Motavalli M 2013 Flexural and interfacial behaviour of metallic beams strengthened by prestressed bonded plates *Composite Structures* **101** pp 22–34
- [12] Siwowski T and Pasko P 2014 Research on the new CFRP prestressing system for metal bridge strengthening *Proc. 15th European Bridge Conf. at Structural Faults & Repair (London)* on CD pp 1-8
- [13] Ghafoori E and Motavalli M 2015 Innovative CFRP - prestressing system for strengthening metallic structures *Journal of Composites for Construction* **19** pp 04015006-1-14.
- [14] Siwowski T and Siwowska P 2018 Experimental study on CFRP-strengthened steel beams *Composites Part B: Engineering* **149** pp 12-12
- [15] Tavakolizadeh M and Saadatmanesh H 2001 Galvanic corrosion of carbon and steel in aggressive environment *Journal of Composites for Construction* **5** pp 200–210
- [16] Piatek B, Siwowski T, Michalowski J and Blazewicz S 2018 The flexural strengthening of RC beams with prestressed CFRP strips: Development of a novel anchor & tensioning system *Journal of Composites for Construction* (in press)