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Flexural response of HSC girders strengthened with non- and prestressed CFRP laminates

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SUMMARY

An experimental programme was carried out to characterise the flexural response of prestressed high-strength concrete (HSC) girders strengthened with CFRP laminates. For that purpose, four beams with 20 m span were subjected to four-point bending loads and the effectiveness of two distinct strengthening strategies was analysed. The following testing situations have been considered: one girder was externally strengthened with CFRP laminates, whereas one was externally strengthened with prestressed CFRP laminates; the two remaining girders were left unstrengthened and were used as control. The monitoring system included the measurement of deflections at critical sections, strains in pre-selected points of the concrete girder and CFRP laminates and the applied loading, respectively using displacement transducers, strain gages and load cells. Herein, the tests are thoroughly described and the most relevant results and conclusions are presented.

1. INTRODUCTION

The use of fibre reinforced polymer (FRP) materials in the context of retrofitting structures started in the 1980s, mainly by means of using the externally bonded reinforcement (EBR) technique. Considerable investigation, guidelines and practical applications have been devoted to reinforced concrete (RC) structures of low or medium-strength concrete [1]. More recently high-strength concrete (HSC) has been introduced in RC structures. For this type of materials/structures current knowledge in terms their future rehabilitation is still missing.

Fernandes [2] conducted a study to assess the feasibility of prefabricating long-span prestressed girders with HSC. In this context 4 girders with I-shaped cross-section and 20 m span were casted (see Figure 1). The HSC developed conducted to high slenderness and ductility girders. Two girders were submitted to flexural tests up to the failure and the remaining two were studied in terms of long-term behaviour (creep, shrinkage and losses) [3].

The use of prestressed FRP materials also started at the end of 1980s [1]. Prestressing FRP for strengthening RC structures combines the benefits of passive EBR FRP systems with the advantages associated with external prestressing. Over the last two decades prestressed FRP has been used to strengthen RC structures and considerable advantages have been pointed out, not only at serviceability, but also at ultimate limit states [4]. Up to now, three mainly procedures have been developed to apply prestress in the FRP [4]: cambered prestressing systems, prestressing against an independent element and prestressing against the element to be strengthened. Special end-anchorages are required at the ends of the prestressed FRP element to transfer the high shear stresses. The proposed end-anchorage systems can be divided in three categories [5]: metallic anchors, non-metallic anchors and the gradient anchorage method. The first two systems have been developed worldwide, whereas the latter has been proposed and developed by Empa – Swiss Federal Laboratories for Materials Science and Technology [6].

The present work aims at contributing to the knowledge on the flexural rehabilitation of HSC girders strengthened with EBR CFRP laminates. In addition to that, the influence of using non-prestressed and prestressed CFRP laminates is also assessed.

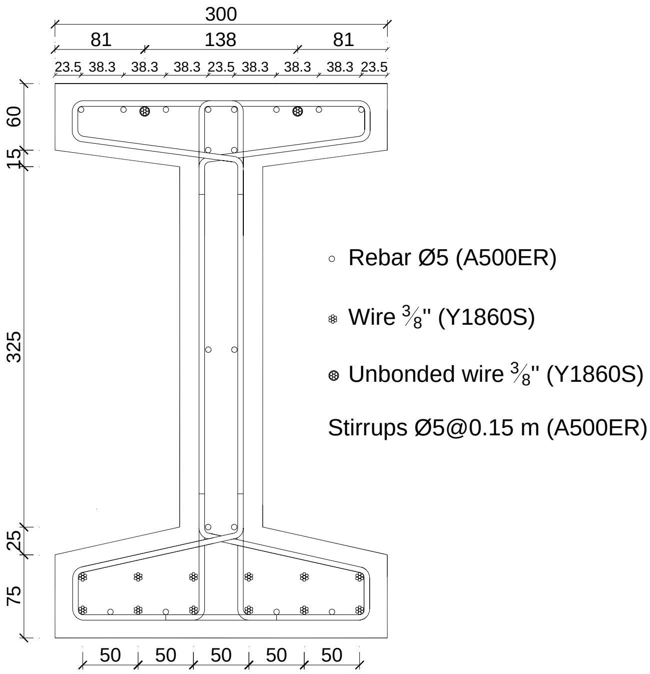


Figure 1: Cross-section of the unstrengthened girders [2]. Note: all units in [mm].

2. EXPERIMENTAL PROGRAMME

The experimental programme included four identical girders. Two specimens were used as reference girders (REF1 and REF2) [2] and the other two were strengthened with non-prestressed and prestressed CFRP laminates (STR_NON and STR_PRE) [7, 8]. In the following sections, specimens and experimental set-up, material characterisation, preparation of specimens and loading, are described.

2.1 Specimens and test set-up

The selected girders have 20 m span, I-shaped cross-section, and have been tested according to the set-up represented in Figure 1. The longitudinal reinforcement is composed by 19 rebars of 5 mm diameter, 12 pre-tensioned strands at the bottom flange and 2 unbonded post-tensioned strands at the top flange. The transverse reinforcement is composed by 5 mm rebars with a longitudinal spacing of 150 mm. The girders were subjected to four-point bending loads with a total span length and shear span of 19.66 m and 6.82 m, respectively (see Figure 2).

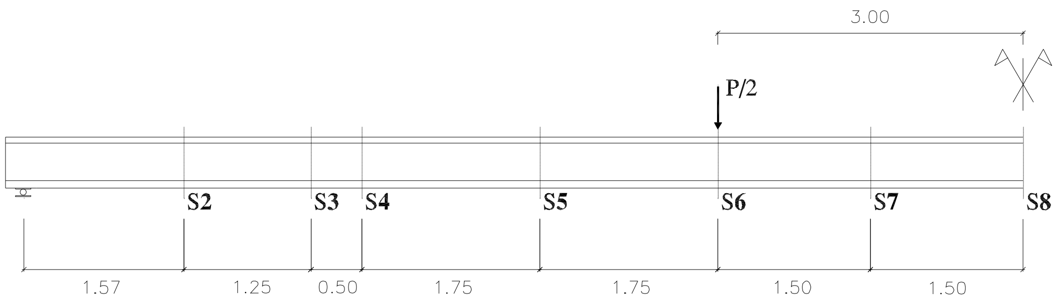


Figure 2: Experimental set-up and instrumented sections. Note: all units in [m].

The internal transducer of the actuator (Servosis® with a capacity of 1000 kN and 300 mm of stroke) was used to control the test with a velocity of 0.25 mm/s. Several displacement transducers were used to measure the vertical displacements along the girder (S6, S7 and S8), as well as the strains in the longitudinal steel reinforcements (S2, S4, S5, S7 e S8) and in the CFRP (S2, S3, S6 and S8).

2.2 Material characterisation

The mechanical properties of the HSC as well as the reinforcing and prestressing steel are presented in Tables 1 and 2, respectively.

The CFRP laminate used in the present work, with 1.4 mm thick and 100 mm wide, and a trademark CFK 150/2000, was provided in rolls of 100 m each by S&P® Clever Reinforcement Company. This laminate is composed of unidirectional carbon fibres and epoxy vinylester resin, and has a smooth external surface. The mechanical properties provided by the supplier are presented in Table 3.

In the present experimental programme a thixotropic, grey two-component (A and B), epoxy resin produced by S&P® Clever Reinforcement Company was used to bond the laminates to concrete. According to the supplier this adhesive with the trademark "S&P Resin 220 epoxy resin" has the main properties included in Table 4.

Table 1: Mechanical properties of the HSC (average values).

Material	***Density*** [kN/m^3]	***Compressive strength*** [MPa]	***Young's modulus*** [GPa]	***Tensile strength*** [MPa]
HSC (28 days)	26.2	124.9*	60.1	5.5

* Value from compression tests with cubes with 150 mm.

Table 2: Mechanical properties of the reinforcements (average values).

Material	***Yield Strength*** [MPa]	***Tensile strength*** [MPa]	***Young's modulus*** [GPa]	***Strain at Failure*** [‰]
A500ER (Ø5)	604	646	200	115
Y1869(3/8")	1944	2043	196.9	57.9

Table 3: Mechanical properties of the CFRP laminates (average values).

Material	***Young's modulus*** [GPa]	***Tensile Strength*** [MPa]
S&P® CFK 150/2000	165	> 2000

Table 4: Physical and mechanical properties of the epoxy adhesive (average values).

Material	***Components***	***Mixing ratio***	***Adhesive strength*** [MPa]	***Young's modulus*** [GPa]	***Tensile Strength*** [MPa]
S&P® Resin 220 epoxy resin	A (resin) and B (hardener)	4 : 1 (A : B) by weight or volume	> 3 MPa*	7.7**	20.6**

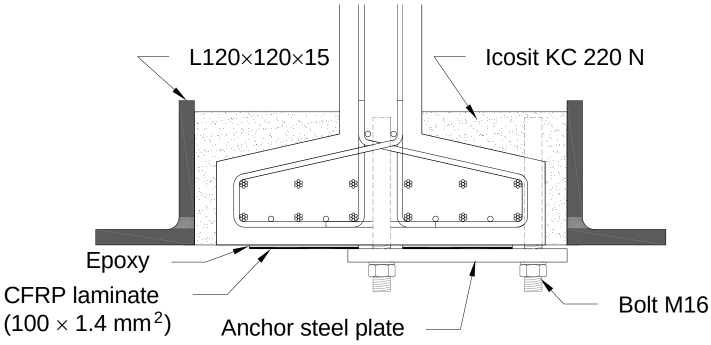
* Value given by the supplier; ** Characterisation performed according to the ISO 527-2:1993 [9].

2.3 Strengthening solution
Several numerical simulations were carried out in order to find out a proper strengthening solution [10]. Two CFK 150/2000 laminates with a rectangular cross-section of 100×1.4 mm^2 were adopted to strengthen the girders, mainly due to geometrical limitations of the girders (width of 300 mm).

Eq. (1) defines the equivalent longitudinal steel reinforcement ratio, $\rho_{s,eq}$, where b is the width of the beam; A_s, A_p and A_f are the cross sectional area of the tensile longitudinal steel bars, prestressed strands and FRP systems, respectively; E_s, E_p and E_f are the Young's modulus of steel, prestressed strands and FRP, respectively; and, d_s, d_p and d_f are the distance from the top concrete compression fibre to the centroid of the steel bars, prestressed strands and FRP systems. In the present work $\rho_{s,eq}$=0.67% (0.15% – FRP system) which is slightly high when compared with values existing in the literature.

$$\rho_{s,eq} = \left(\frac{A_s}{bd_s} + \frac{E_p}{E_s} \cdot \frac{A_p}{bd_p} \right) + \frac{E_f}{E_s} \cdot \frac{A_f}{bd_f} \tag{1}$$

2.4 Preparation of specimens and loading
The surface preparation included the grinding of the surface to be strengthened with CFRP laminates in order to improve the bond conditions. In addition to that, the girder strengthened with prestressed laminates had both extremities enlarged in order to temporarily accommodate the prestressing devices and to assure a minimum area surrounding the M16 bolts (see Figures 3 and 4). This procedure was required due to the small width of the girders (300 mm) and was basically composed by two L-shaped steel profiles (120×120×14 mm^3) glued to the existing girder with Icosit® KC 220 N. To improve the connection between the steel profile and the Icosit, bolts M12 were also used (see Figure 3b). More details about these steps can be found in [10].



(a)


(b)

Figure 3: Enlargement at both extremities of the girders to be strengthened with prestressed laminates: (a) schematic representation; (b) picture.

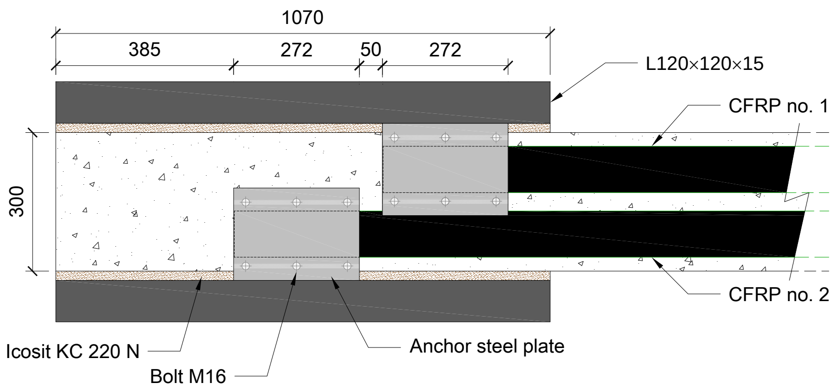
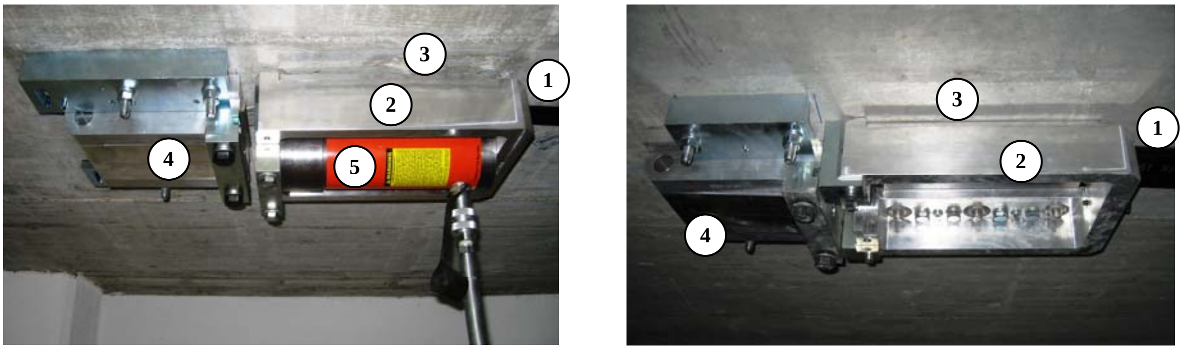


Figure 4: Bottom view of the enlargement. Note: all units in [mm].

A 40 kN pre-load was applied to the girders before strengthening STR_NON and STR_PRE due to the pre-camber caused by the existing prestress. The pre-load value was defined assuming a quasi-permanent load combination from design project. At the end of this step the girder was properly anchored to prevent the recovery of the imposed deflection/load, as shown in Figure 5.

Figure 5: Pre-load of the beam.

The commercial system proposed by S&P® Clever Reinforcement Company for prestressing the CFRP laminate was used in the present work. Figure 6 shows the main devices composing the system. Depending on the level of deformation of the laminate during the prestressing, both or only one anchor can be active. This system requires the use of permanent end-anchorage steel plates. The location of the end-anchorage steel plates is shown in Figure 4 for the present experimental programme.



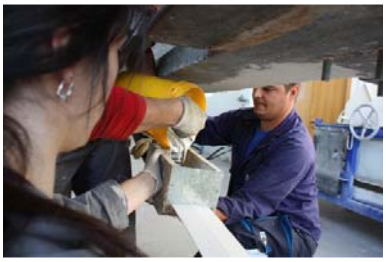
(a) (b)

Figure 6: (a) Active anchor; (b) Passive anchor. 1- Laminate; 2- Frame; 3- Anchor steel plate; 4- Clamp; 5- Hydraulic cylinder.

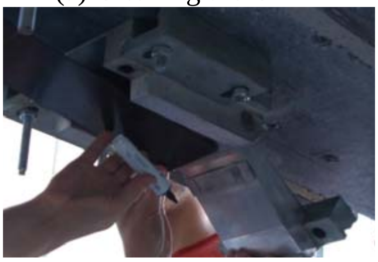
According to the literature, the effective use of the tensile strength of the composite requires a prestressing level of approximately 0.50 of the CFRP ultimate strength, f_{fu}, according to [11]. For prestressing levels above $0.70f_{fu}$, failure occurred by fracture of the composite. On the other hand, for prestressing levels below $0.60f_{fu}$, strip debonding is the most commonly observed failure mode [11]. A minimum value of $0.25f_{fu}$ is suggested to take advantage of using the prestressing. In the present work a prestressing strain of 0.4% was adopted, which corresponds to $0.30\text{-}0.35f_{fu}$.

Figure 7 shows the main steps adopted for strengthening the girders. First of all the CFRP laminates were cleaned with acetone (see Figure 7a). Then the epoxy adhesive was prepared according to the technical sheet and was applied on the CFRP laminate surface using the box shown in Figure 7b. This box had two main purposes: i) to apply the epoxy in an easy and fast way; and, ii) to assure (Figure 7c) a uniform layer of epoxy with approximately 2 mm of thickness in both longitudinal and transverse directions. Then, the laminate was fixed to the clamp at both extremities (Figure 7d) and finally, the prestressed was applied (see Figures 7e and f). The sequence of prestressing the laminates is depicted in Figure 4, corresponding the latter to laminate no. 2.


(a) Cleaning the CFRP


(b) Application of the adhesive


(c) Placing the CFRP


(d) Fixing the laminate at the clamp


(e) Active anchorage

(f) Prestressing the laminates with the hydraulic pump

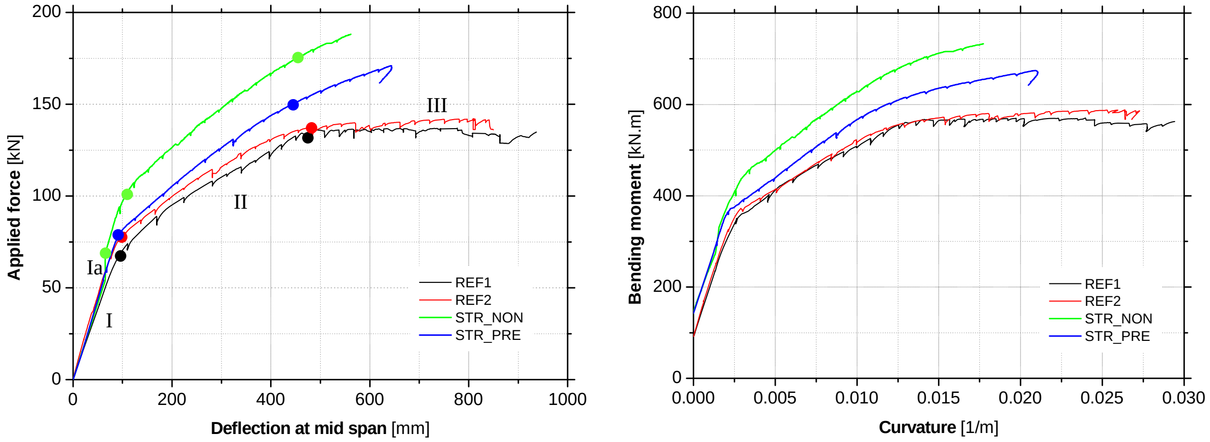
Figure 7: Main steps followed for the application of the prestressed CFRP laminates.

3. RESULTS

Figure 8 shows the force *versus* deflection and bending moment *versus* corresponding curvature, both at mid span, whereas Table 5 summarises the characteristic points from these charts. In this table, F_{cr}, F_y, and F_{max} are the cracking, yield initiation and maximum loads, respectively, and δ_{cr}, δ_y, and δ_{ult} are the corresponding vertical displacements at mid-span for F_{cr}, F_y, and ultimate displacement.

With the exception of girder STR_PRE, all the remaining girders have similar elastic stages (I) – see Figure 8a. In this stage, the stiffness variation with the FRP is almost negligible for the case of girder STR_NON. Girder STR_PRE experienced two distinct behaviours in the elastic stage: stage I similar to the other girders and stage Ia, which is characterised by a force growth of about 13 kN without changing the deflection due to the application of the prestress. The average stiffness of girders REF1, REF2 and STR_NON, in the elastic stage, is about 810 N/mm, whereas for girder STR_PRE is about 913 N/mm, which is approximately 13% higher. It is clear that the strengthening increased the crack initiation loading. A significant increment is observed for the case of the STR_PRE (38%), revealing one of the important advantages of using prestressed CFRP laminates. As expected, after crack initiation, girders REF1 and REF2 have similar stiffness, which is slightly lower than the strengthened girders. The yield initiation of the longitudinal steel reinforcements is clearly identified for the case of the unstrengthened girders (stages II to III). For girders STR_NON and STR_PRE, however, this transition is not straightforwardly identified. The determination of these points for these girders performed by evaluating the slopes in stages II and III.

According to the obtained values (see Table 5), and as expected, a significant increment (30%) in terms of F_y is observed for the case of girder STR_PRE when compared with the reference girders. When girders STR_PRE and STR_NON are compared, the prestress increased F_y, at about 17%. The marginal variation of δ_y for the strengthened girders was unexpected and is not reported in the literature. The strengthening solutions increased the load carrying capacity (F_{max}) at about 22% and 35%, respectively, for girders STR_NON and STR_PRE, when compared with the reference girders. The benefit of prestressing the CFRP laminates was lower (at about 10%), when compared with the value obtained at F_y level. This lower performance can be related to the premature failure that occurred in all strengthened girders. In fact, failure always started by concrete crushing at mid span in the vicinity of the top flange, followed by a major crack crossing the entire cross-section, as shown in Figure 9. During the tests, several flexural cracks were observed, starting from the bottom flange and gradually growing towards the web.



(a) (b)

Figure 8: (a) Deflection at mid span *versus* applied force and (b) bending moment *versus* curvature.

Table 5: Summary of the obtained results.

Girder	δ_{cr} [mm]	F_{cr} [kN]	δ_y [mm]	F_y [kN]	δ_{ult} [mm]	F_{max} [kN]
REF1	101.6	71.3	464.4	134.2	936.0	137.0
REF2	96.3	77.1	439.9	134.7	849.6	142.2
STR_NON	99.5 (1%)*	80.8 (9%)*	445.9 (-1%)*	149.9 (11%)*	643.1 (-28%)*	170.9 (22%)*
STR_PRE	111.2 (12%)*	102.3 (38%)*	451.7 (0%)*	175.1 (30%)*	561.7 (-37%)*	188.1 (35%)*

* Variation of the analysed parameter when compared with the average of the reference girders

Figure 9: Failure mode observed in girder STR_PRE.

Figure 10 shows the evolution of the strains in the CFRP laminate at the girder mid-span (section S8 – see Figure 2) with the applied force. It is clear that at beginning the strains do not change with loading, since the strengthening was applied with a predefined load level (see also Section 2.4). As expected, the strains increased with the applied load. At the maximum load the strain level was 6.5‰ and 9.2‰ for girders STR_NON and STR_PRE, respectively. In spite of the former value being quite acceptable for passive strengthening, the latter value did not kept the initial strain gap of 4.0‰. Although of 9.2‰ be a satisfactory in EBR strengthening systems, a better performance was expected. No reasonable explanation was found for this behaviour.

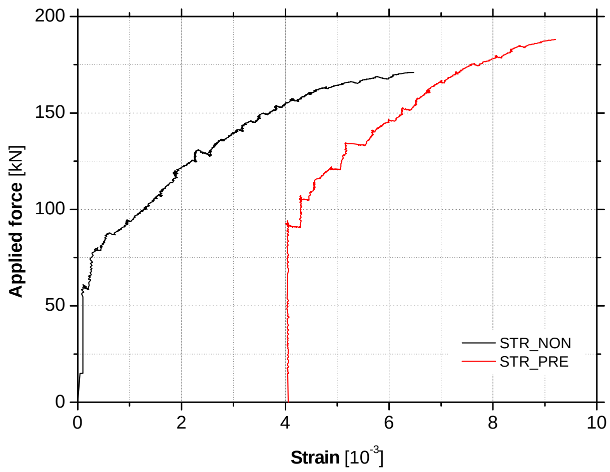


Figure 10: CFRP strain *versus* applied load at mid-span cross-section.

4. CONCLUSIONS

With the aim of studying the flexural behaviour of prestressed high-strength concrete (HSC) long-span girders strengthened with FRP materials, an experimental programme composed by 4 girders, was carried out. Two girders were used as reference (REF), the third girder was externally strengthened using two CFRP laminates (STR_NON) and, finally, the fourth girder was externally strengthened with two prestressed CFRP laminates (STR_PRE). From this experimental programme the following main conclusions can be pointed out:

- with the strengthening solutions the load carrying capacity increased 22% and 35% for girders STR_NON and STR_PRE, respectively, when compared with the reference girders;
- when compared with the REF girders, the stiffness before yielding initiation of the longitudinal steel bars of girders STR_NON and STR_PRE only slightly changed; however after this point, a significant variation was observed, as expected;
- the benefits of prestressing the CFRP laminates were materialised not only in terms of strength, but also in terms of stiffness, at different levels: crack initiation, yield initiation of the longitudinal steel bars and ultimate load;
- in the girder STR_NON, the strain level at the CFRP reached 6.5‰, whereas for the case of STR_PRE a 9.2‰ strain level was attained;
- the girders failed by concrete crushing at the top flange.

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REFERENCES

[1] Bakis, C.E.; Bank, L.C.; Brown, V.L.; Cosenza, E.; Davalos, J.F.; Lesko, J.J.; Machida, A.; Rizkalla, S.H.; Triantafillou, T.C. (2002) “Fiber-Reinforced Polymer Composites for Construction — State-of-the-Art Review.” Journal of Composites for Construction, 6(2): 73-87.

[2] Fernandes, P. (2007) “Girders with high span prefabricated with prestressed HSC - Feasibility, Design, Construction and Behavior”. Ph.D. thesis, Faculty of Science and Technology of the University of Coimbra, Portugal (in Portuguese).

[3] Fernandes, P.; Júlio, E.; Tiago, P. (2010). "Time-dependent behaviour of precast long-span prestressed high strength concrete girders". BE2010 – Encontro Nacional de Betão Estrutural 2010, Lisbon, Portugal (in Portuguese).
[4] El-Hacha, R.; Wight, R.G.; Green, M.F. (2001) "Prestressed fibre-reinforced polymer laminates for strengthening structures." Progress in Structural Engineering and Materials, 3(2): 111-121.
[5] Michels, J.; Sena-Cruz, J.; Czaderski, C.; Motavalli, M. (2012) "Structural strengthening with prestressed CFRP strips anchored with the gradient anchorage method" Composites for Construction, Submitted.
[6] Motavalli, M.; Czaderski, C.; Pfyl-Lang, K. (2011) "Prestressed CFRP for Strengthening of Reinforced Concrete Structures: Recent Developments at Empa, Switzerland." Journal of Composites for Construction, 15(2): 194-204.
[7] Fernandes, C. (2011) "Study of precast long-span prestressed high-strength concrete girders strengthened with CFRP laminates". M.Sc. thesis, Faculty of Science and Technology of the University of Coimbra, Portugal (in Portuguese).
[8] Fernandes, C.; Fernandes, P.; Silva, P.; Dias-da-Costa, D.; Sena-Cruz, J. and Júlio, E. (2012) "Failure behaviour of high strength concrete girders strengthened with CFRP". BE2012 – Encontro Nacional de Betão Estrutural 2012, Oporto, Portugal (in Portuguese).
[9] Sena-Cruz, J.M.; Michels, J.; Czaderski, C.; Motavalli, M.; Castro, F. (2012) "Mechanical behavior of epoxy adhesives cured at high temperatures", Report no. 880163, Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland, 40 pp.
[10] Silva, P. (2011) "Numerical and experimental study with girders of large span prefabricated with high-strength concrete prestressed and strengthened with FRP" MSc thesis, University of Minho, 143 pp. (in Portuguese)
[11] Kotynia, R.; Walendziak, R.; Stoecklin, I.; Meier, U. (2011). "RC Slabs strengthened with Prestressed and Gradually Anchored CFRP Strips under Monotic and Cyclic Loading." Journal of Composites for Construction, 15(2): 168-180.