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RC beams strengthened with prestressed and gradually anchored CFRP strips

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ABSTRACT: This paper presents an experimental and numerical investigation on the load bearing capacity of 6.5m-long RC beams strengthened with prestressed CFRP strips with gradient anchorage. This technique eventually leaves a purely concrete-epoxy-strip connection without any remaining mechanical devices such as bolts or plates. Laboratory tests were carried out in the framework of an industry-based R&D project.

Experimental testing consisted of a 6-point static loading procedure on four simply supported beams. Experimental results, such as force-deflection, force-strain curves, and failure modes, are presented. In a second step, a non-commercial finite element code is presented and applied to the previously presented testing configuration. Finally, the experimental results and the corresponding numerical simulations are compared.

1 INTRODUCTION

Whereas externally bonded and unstressed Carbon Fiber Reinforced Polymer (CFRP) strips can be considered as 'state-of-the-art' in structural retrofitting, their application at a prestressed state represents a newer technique. In this context, an important issue is the anchorage at the strip ends. Considerable research and development in this direction has been made at Empa since the introduction of the 'Gradient Anchorage' by Professor Urs Meier (Meier et al. (2001), Motavalli et al. (2011)). This innovation allows a pure epoxy-based connection between the strip and the concrete substrate. The prestressing force in the strip is gradually decreased towards zero at both ends by a step-wise accelerated epoxy curing at high temperatures (Michels et al., (2012a)). A detailed description of the strengthening procedure can be found in Michels et al. (2013).

This paper presents an experimental investigation on large-scale RC beams strengthened by prestressed CFRP strips installed with the mentioned gradient anchorage. The tests were conducted in the framework of an industry-based R&D project, aiming at developing a new heating device for accelerated adhesive curing (Michels et al., (2012b)) for on-site applications.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials, geometry and strengthening

2.1.1 Beam geometry and materials

The tested beams have a total length of 6500 mm. Width and height were 1000 and 220 mm, respectively. Upper and lower steel reinforcement were each time 7∅8 mm steel bars. Stirrups of ∅8 were installed every 150 mm with the exception of the central 1200 mm part (Figure 1).

Concrete compressive strength on cube after 28 days $f_{c,cube,28}$ as well as on the testing day $f_{c,cube,test}$ is given in Table 1. Mean steel yielding strength $f_{s,y}$ was 540 MPa and ultimate tensile strength $f_{s,u}$ 619 MPa. CFRP unidirectional tensile strength $f_{f,u}$ was 2544 MPa and its elastic modulus E_f was 157.8 GPa according to the distributor's technical data sheet.

Table 1 Concrete compressive strengths on cube (*estimated according to *fib* bulletin 1 (fib (1999))

Beam	$f_{cm,cube,28}$ [MPa]	$f_{c,cube,test}$ [MPa]
1	56.8	63.2
2	54.3	57.7
3	52.2	54
4	54.1	69.4*

2.1.2 Retrofitting procedure

All beams were strengthened with a CFRP strip (carbon fiber type Tenax/Toho and vinylester-based matrix by Huntsman) from S&P Clever Reinforcement Company. Thickness t_f was 1.22 mm and width b_f was 100 mm. An initially imposed strain $\varepsilon_{f,p}$ of 6 ‰ (0.006) was applied by the new prestressing system, which was developed at Empa in collaboration with the industrial partner. The gradient anchorage of the strip was simultaneously performed on both strip ends. The total prestress force F_p of 120 kN was released in three steps: 50 kN over a bond length l_b of 300 mm and twice 35 kN over a bond length of each time 200 mm. A supplementary safety length of 100 mm without any remaining shear stress was added also under accelerated curing at the very strip end.

The following characteristics have to be remembered when commenting the experimental results:

-*Beam 1&3*: strip application was performed the conventional way, i.e. strengthening 'overhead' as on real-case structures. No special treatment of the strip was performed.

-*Beam 2*: the CFRP strip was grinded at both ends with the aim to roughen the contact surface for a better bond behavior.

-*Beam 4*: strip application was in this case not applied 'overhead', but 'top-down' on the upper casting surface. In this case, prestressing does not counteract deflections due to dead-loads. Additionally, doubts about the quality of the concrete grinding have to be expressed.

2.2 Test setup

The test setup is shown in Figure 2. The beams were simply supported with a total span L of 6 m. Two actuators apply in total 4 points loads F equally distributed every 1.2 m over the total beam length. Load cells under each jack measured and recorded the forces during the failure test. The tests were performed under displacement control with a loading speed of 3 mm/min. Two LVDTs were used to capture vertical deflection at midspan. In addition to the strain gauges SG1 and 4 installed prior to the strengthening process to measure the prestrain, four additional gauges were mounted before static loading (three for Beam 4, SG6 omitted in this case). For evaluation, the mean strain between SG1 and SG4 shortly before the start of the loading test was added to the measured values of the remaining strain gauges 2, 3, 5 and 6. The exact location of all measurements and the CFRP strip is given in Figure 1.

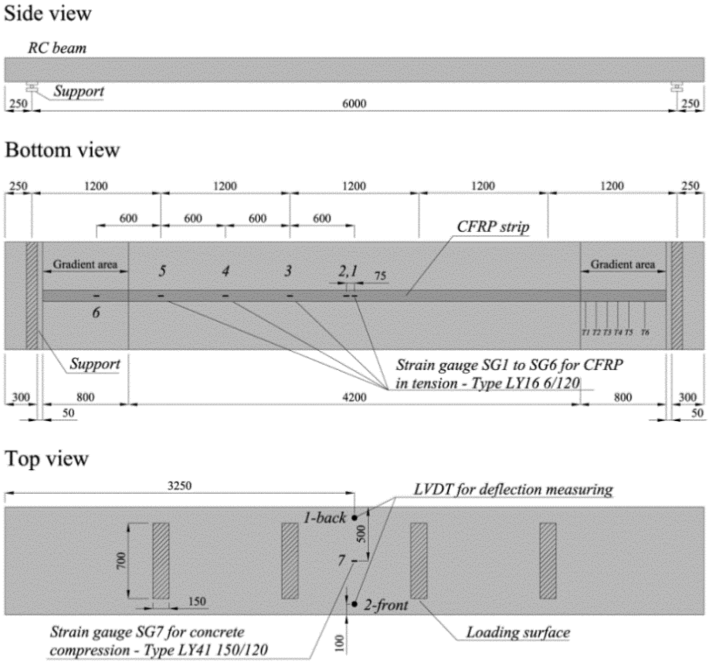

Figure 1 Measurement locations

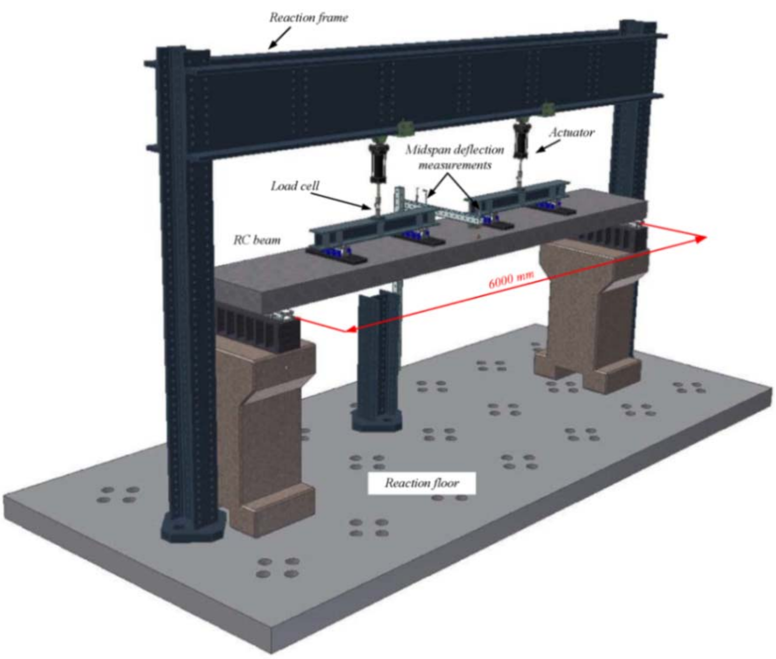

Figure 2 Test setup for 6-point bending

2.3 *Experimental results*

Total force-deflection (F_{tot}=4*F)* and total force-strain curves of Beam 2, 3 and 4 are presented in Figure 3. Due to an electronic issue with the measurement device, no forces were recorded for Beam 1 (deflection and strains are available, the ultimate bearing load was approximately 80 kN). All key results are summarized in Table 2.

It is clearly visible that Beams 1 and 3 exhibit the highest bearing capacity with approximately 80 kN compared to a total force of more or less 70 kN for Beams 2 and 4. In both cases, the maximum bearing load come along with maximum tensile strains in the CFRP strip of 14.2 and 13.8 ‰, equivalent to approximately 90 % of the failure strain. Beams 1, 2 and 3 failed by delamination between the CFRP strip and the underlying epoxy layer in the gradient anchorage (see Figure 4). Due to the differences in bearing forces (and related maximum CFRP strains), it can be concluded that the initial grinding of the strip in the gradient area for Beam 2 was detrimental to the bond strength between the two components laminate and resin. Beam 4 seemed to fail by strip delamination of the externally bonded reinforcement in the concrete substrate. The reason for this earlier failure compared to Beams 1 and 3 might be a minor concrete quality, as the initial upper casting surface was used as bottom/tensile surface for the strengthening and loading, and/or a low quality of the concrete grinding procedure.

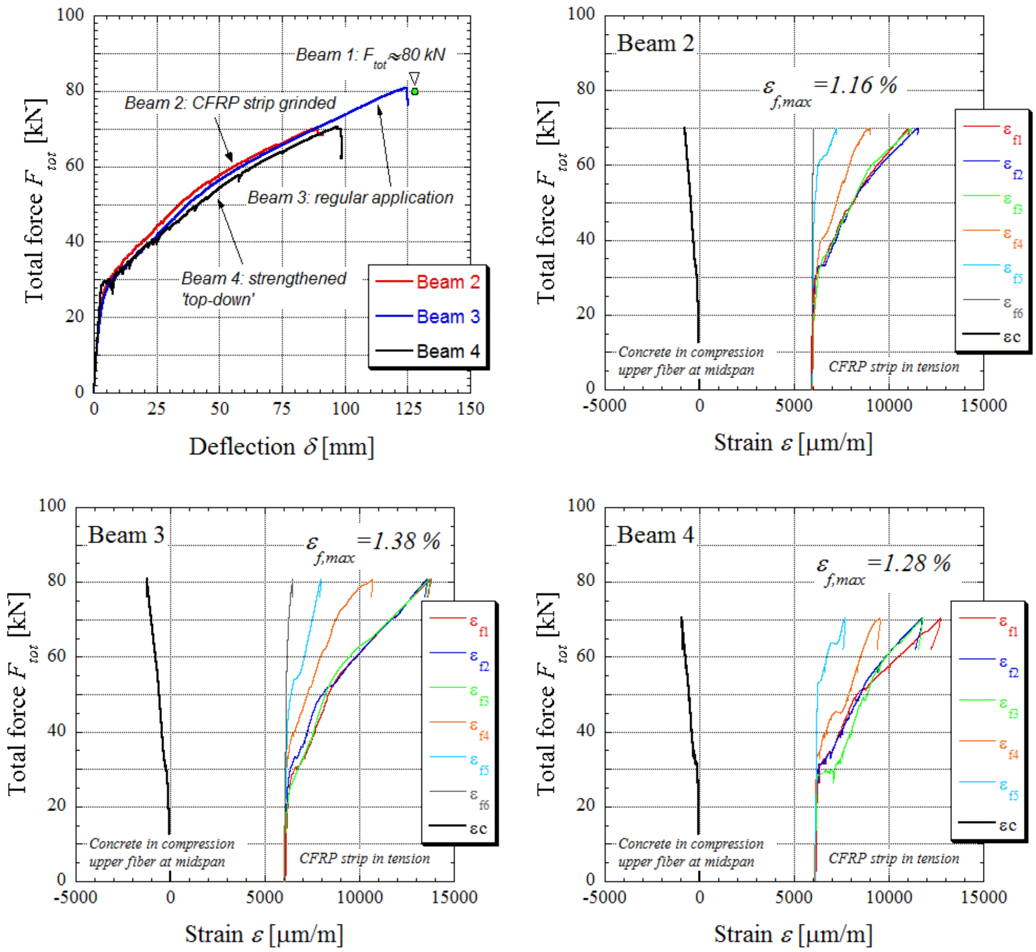

Figure 3 Total force-deflection and total force-strain curves for Beams 2, 3 and 4

Locations of the last cracks l_{cr} measured from the support end of Table 2 indicate that no cracking occurred inside the gradient area, which starts at 50 mm from the support location up to a total length of 800 mm (see Figure 1).

Table 2 Key results from the static loading tests ($\varepsilon_{f,p}$=prestrain, F_{tot}=total force, δ_u=midspan deflection at failure, $\Delta\varepsilon_f$=additional CFRP tensile strain up to the failure load, l_{cr}=position of last crack with regard to the support (mean value from both sides))

Beam	Prestrain ε_{fp} [%]	Test results F_{tot} [kN]	δ_u [mm]	$\varepsilon_{f,u}$ [%]	$\Delta\varepsilon_f$ [%]	l_{cr} [m]
1	0.59	≈80.0	127.4	1.42	0.83	1.10
2	0.59	69.9	91.2	1.16	0.57	1.15
3	0.60	80.9	125.3	1.38	0.78	1.11
4	0.61	70.5	98.8	1.28	0.67	1.27

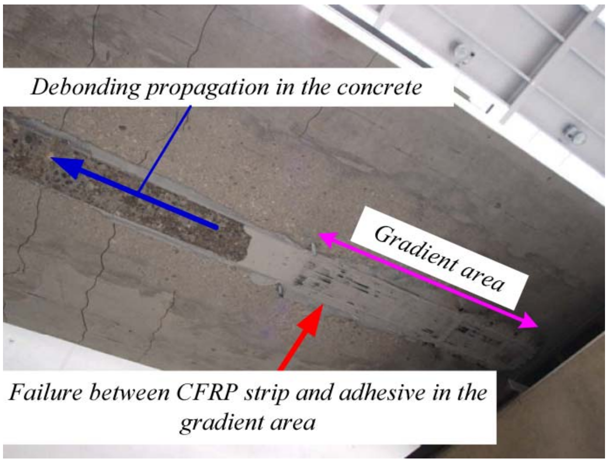

Figure 4 Gradient anchorage failure at the strip/epoxy interface

3 NUMERICAL CODE

Numerical simulations of the experimental results outlined in the previous section can be performed by means of a 1D finite element (FE) model based on an extension of the one formulated by Faella et al. (2008) for non-prestressed externally bonded FRP-strengthened RC beams. Figure 5 shows the kinematics of the aforementioned finite element whose displacement and force vectors collect the six components described in the following:

$$\boldsymbol{s} = \begin{bmatrix} v_i & \varphi_i & s_i & v_j & \varphi_j & s_j \end{bmatrix}^T \tag{1}$$

$$\boldsymbol{Q} = \begin{bmatrix} V_i & M_i & F_i & V_j & M_j & F_j \end{bmatrix}^T \tag{2}$$

which are represented in Figure 5.

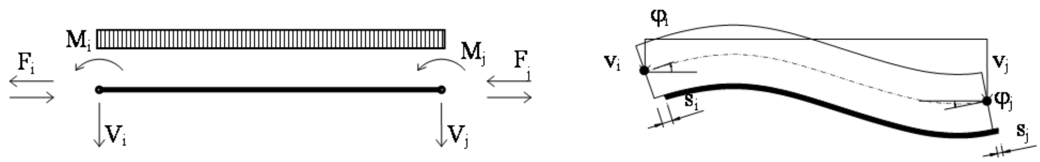

Figure 5 Kinematics and degrees of freedom of the proposed finite element

The force and displacement vectors are related by means of the following usual matrix expression:

$$\boldsymbol{Q} = \boldsymbol{K}\boldsymbol{s} + \boldsymbol{Q}_0 \tag{3}$$

where $\boldsymbol{K}$ is the so-called stiffness matrix and $\boldsymbol{Q}_0$ is the vector of equivalent nodal forces. Since the model under consideration derives from the well-known Newmark's theory for two-layer beams in partial interaction, an "exact" expression is available for both $\boldsymbol{K}$ and $\boldsymbol{Q}_0$ (Martinelli et al., 2012) which takes into account both shear-flexibility of the connected layers and the partial interaction resulting by their flexible interface. As a matter of principle, such a solution completely defines the matrix $\boldsymbol{K}$ and the contribution $\boldsymbol{Q}_{0,q}$ of transverse distributed loads to the vector $\boldsymbol{Q}_0$. Then, the complete expression of the vector $\boldsymbol{Q}_0$ for the problem under consideration, should also cover the effect of the initial strain $\varepsilon^{*}_{f,p}$ which represents the axial strain imposed to the FRP strip to apply the pre-stressing action to the RC beam. Although mathematical details about the whole derivation of the contribution $\boldsymbol{Q}_{0,p}$ corresponding to the pre-stressing action cannot be reported herein due to space constraints, it is easy to recognize that the final analytical expression of $\boldsymbol{Q}_0$ can be written as follows:

$$\boldsymbol{Q}_0 = \boldsymbol{Q}_{0,q} + \boldsymbol{Q}_{0,p} \approx \boldsymbol{Q}_{0,q} + EA_f \cdot \begin{bmatrix} 0 & -d & -1 & 0 & d & 1 \end{bmatrix}^T \tag{4}$$

where EA_f is the axial stiffness of the FRP strip and d the distance between the transverse section centroid of the RC beam and FRP strip.

The 1D FE formulated through eqs. (3) and (4) can be conveniently utilized to perform linear analyses of beams strengthened in bending by externally-bonded pre-stressed FRP strips. However, due to the nonlinear nature of both the stress-strain relationships which describe the behavior of structural materials (i.e. concrete and steel) and the bond-slip relationship which characterizes the FRP-to-concrete interface, a secant updating procedure can be implemented to simulate the behavior of RC beams with externally prestressed FRP strips, as well as already done for non-prestressed ones (Faella et al. (2008)). Additionally to the failure modes governed by compression failure of concrete, tensile failure of the inner steel reinforcement, tensile failure of the CFRP strip, a bond stress-slip relation was considered at the two-layer interface according to the results given in Czaderski et al. (2012).

Figure 6 (left) presents the comparison between the experimental results in terms of applied force F_{tot} and midspan displacement δ measured after having applied the prestressed CFRP strip. A very good agreement can be observed between the results observation and the numerical simulation which stopped when the maximum axial strain ε_f=0.016 was achieved in the FRP strip. This indicates a tensile failure of the CFRP strip in tension. Compared to the experimental results, the numerical model slightly overestimates the final bearing capacity of the beam. The same figure also depicts the simulation of a similar beam, possibly tested without pre-stressing action (not tested): the significant difference in terms of cracking and yielding load (with respect to the prestressed beam) points out the importance of prestressing in recovering a significant part of the stresses induced by the dead loads (just the self-weights in this experimental case). On the right side of Figure 6, the numerical values of the increasing strain ε_f with growing load are presented. It can be seen that no cracks and therefore no significant strain increase can be noticed in the gradient anchorage area. This was confirmed by the location of the last cracks shown in Table 2 by visual inspection after the test end. Eventually, a comparison between the experimental and numerical CFRP tensile strain evolution with growing outer load F_{tot} is given in Figure 7. Similar to the load-deflection curve, a slight overestimation of the cracking load for the numerical model can be observed. Subsequently, a very good concordance between experimental values and numerical predictions is noticed.

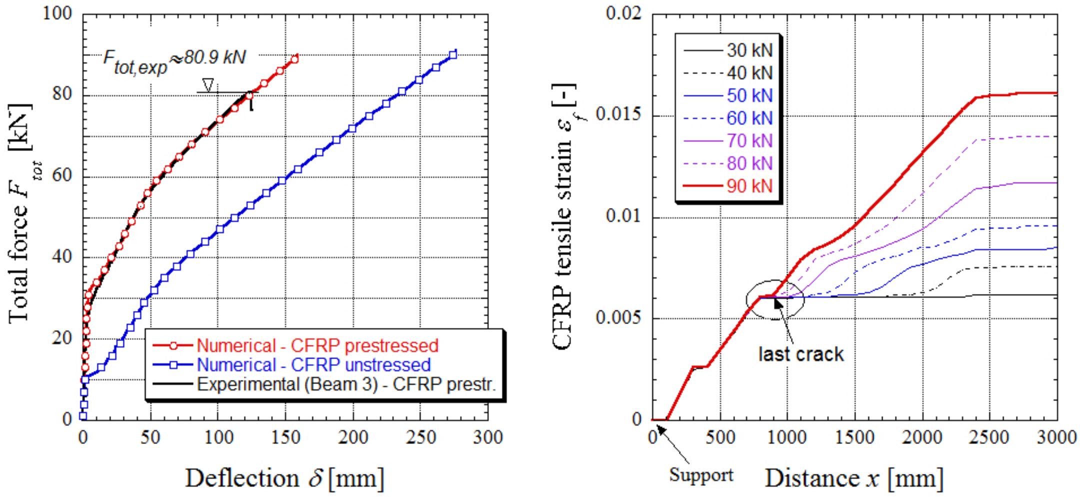

Figure 6 Comparison between experimental (Beam 3) and numerical force-deflection curves (left) and CFRP tensile strain ε_f distribution over half the span under growing outer force (right)

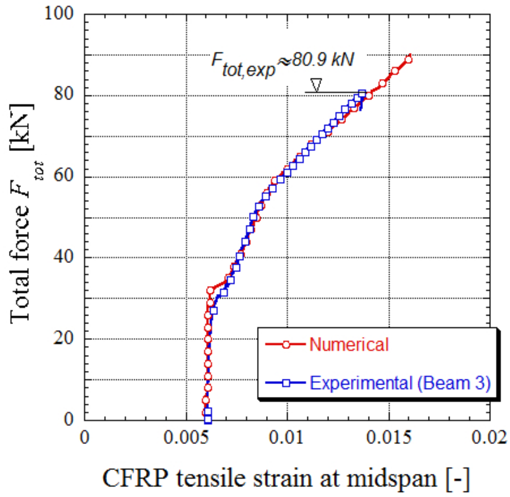

Figure 7 Comparison between experimental and numerical evolution of the CFRP tensile strain at midspan

4 CONCLUSIONS

The experimental and numerical results presented in this paper allow to draw a certain number of conclusions:

- For short-term static loading such as the previously shown beam tests, the gradient anchorage is an efficient technique when a pure CFRP-epoxy-concrete connection is requested. Tensile failure of the CFRP strip was almost reached. Further experimental analysis with regard to durability questions are of course necessary.
- When the degree of prestressing is carefully chosen, a ductile behavior with a distinct steel yielding can be obtained.
- The presented FE model is an efficient technique for further studies regarding structural behavior of prestressed CFRP systems for structural retrofitting. The numerical results are in good agreement with the experimental curves, despite a slight overestimation of the bearing load. In the numerical model, failure occurs by strip snapping, whereas experiments revealed a strip debonding.

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