PRELOADING EFFECT ON LOAD CAPACITY AND DUCTILITY OF RC BEAMS STRENGTHENED WITH PRESTRESSED CFRP STRIPS

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Abstract  
A paper describes experimental test of reinforced concrete beams strengthened in flexure with prestressed CFRP strips. The aim of the test was to investigate preloading effect on strengthening efficiency. Beams were preloaded to 25% or 75% of the load capacity of a non-strengthened beam. Flexural strengthening of RC beams with prestressed CFRP strips is very effective both in ultimate limit state and serviceability limit state, even in case of members highly exhausted before strengthening. The strengthening allows for significant reduction of concrete strains, mid-span deflection and stiffness increase. Strengthening ratio varied from 1.9 to 2.2 of non-strengthened beam’s load capacity.

Keywords: Carbon fiber reinforced polymer, strengthening, prestressing, externally bonded, RC beams

1. Introduction  
Many research programs conducted on reinforced concrete members strengthened in flexure with fiber reinforced polymers (FRPs) proved quite low efficiency of strengthening, due to a sudden, premature CFRP strips debonding from the concrete surface, induced by flexural cracks [1]. Moreover it was indicated that the efficiency of the non-active externally bonded strengthening depends on the type of the CFRP reinforcement and a distance of the strip’s end from the support, the percentage of longitudinal and lateral steel reinforcement and the distribution of bending moments and shear forces in a strengthened element [1, 2]. Although strengthening with non-prestressed composites increased the load capacity of RC member, it has no significant influence on the serviceability conditions (i.e. cracking moment and deflections). To improve an effect of strengthening on the serviceability limit state and to increase a level of the CFRP tensile strength utilization, prestressing of the CFRP strip has been proposed. This technique allows to reduce deflection of a strengthened element, to reduce width of flexural cracks, stress in longitudinal steel reinforcement, concrete strains and to increase stiffness and load capacity of the structure.
Advantages of active strengthening have been confirmed in numerous experimental tests [2, 3, 4, 5, 6, 7, 8, 9, 10], which stated the minimal level of prestressing as 25% of the CFRP tensile strength [3, 4]. In case of CFRP prestressing to the level above 70% of the tensile strength, failure due to the CFRP rupture was observed. On the other hand, prestressing under 60% of the CFRP tensile strength resulted in failure due to the CFRP debonding from the concrete surface [4]. The most effective level of the CFRP prestressing has been defined as 50-60% of the CFRP tensile strength, which allows to achieve almost simultaneous CFRP debonding and its rupture.

The main problem connected with strengthening of reinforced concrete structures with prestressed CFRP strips is the high shear stress at the end of the strip. The tensile stress in CFRP cannot be transferred to concrete due to its much lower tensile strength. To overcome this problem, mechanically anchored steel plates should be applied.

Pioneer non-mechanically anchored system was developed by Prof. Urs Meier at the EMPA laboratory in Zurich [8].

Strengthening of existing reinforced concrete elements needs consideration of the preloading level of the structure before strengthening. Analysis of the experimental test results published so far shows, that an effect of the preloading level on the strengthening efficiency has been taken into consideration very rarely. To verify this influence, the authors of the paper proposed the test program containing the elements strengthened under two different exhaustion levels, caused by elements’ dead load or additional external load equal of 25% and 75% of non-strengthened member’s load capacity, respectively.

The presented test is a part of a large research program, financed from the European Union Project.

![Static scheme, steel reinforcement and strengthening mode of the beam](image)

Figure 1. Static scheme, steel reinforcement and strengthening mode of the beam
2. Program description

Research program carried out in the laboratory of the Department of Concrete Structures in the Technical University of Lodz contained 3 beams (P3, P4, and P7), each strengthened with prestressed CFRP strips. All members were simply supported over the span of 6000mm, with the cross-section’s of 500x220mm. Ordinary steel reinforcement consisted of four 12mm diameter bars at the beam’s bottom and four bars of 8mm diameter at the top. Transverse reinforcement consisted of 8mm diameter stirrups at 150mm spacing. The beam was strengthened with one CFRP strip of 100x1.24mm cross-section (Figure 1). RC members were tested in six point loading as a simply supported beam.

The main variable parameter was the level of beams’ preloading before strengthening. Beams were strengthened under two different preloading levels provided constantly until epoxy resin reached its full strength. To investigate the beam’s preloading effect, the beams P3 and P7 were strengthened under their dead load (corresponding to the load provided by external forces of $2F_p=6.1\text{kN}$), equal to 25% of load capacity of non-strengthened beam. The beam P4 was strengthened under external load of $2F_p=13.7\text{kN}$, which with a dead load of $2F_p=6.1\text{kN}$ equal to $2F_p=19.8\text{kN}$, that corresponds to 75% of the non-strengthened beam’s capacity.

A type of the CFRP strip anchorage was the second investigated parameter. First two beams were strengthened and anchored using S&P system, consisting of steel plates mounted on a concrete member with steel bolts. The beam P7 was strengthened with the strip fully prestressed and reduced to zero along the anchorage distance of 1000mm length at both strip’s ends. The beams were concreted in two series using concrete class C30/37 (Figure 2a) and strengthened in the set-up. Prior to placing in the set-up steel bolts were installed on the bottom side of the beam for the anchorage system (Figure 2b).

![Figure 2. a) Concreting process, b) preparation of the anchorage system](image)

The CFRP strips were bonded to the concrete surface with the epoxy adhesive. Reaching required stress level in the strip allowed to block the anchorage plates, that were removed after next 12 hours (Figure 3).

![Figure 3. Prestressing CFRP laminates](image)

Beam P7 strengthened with reduced prestressing force at the anchorage length, was fully prestressed and bonded to the concrete in the middle section (3600mm) of the CFRP strip. To
prevent the premature CFRP debonding, after next 72 hours mechanical grippers were installed at the ends of bonded strip’s section. Prestressing force was reduced to zero at the end of 1000mm length. The steel plates were removed from the secured CFRP strip and the non-bonded sections were bonded to the concrete surface without any prestressing force. After next 72 hours mechanical grippers were removed.

The following parameters were registered during the test: concrete strains in the tension and compression zone, steel reinforcement strains in the beam’s midspan, CFRP strains and vertical displacements of the tested beam. Simultaneously, the crack pattern and the crack width were registered. Additionally, the vertical reactions were measured with four force sensors, two under each support.

Prestressing levels of the strip for each member are shown in table 1. In case of the beam P3, after preloading to the level of 2F=25.9kN, six cycles of unloading and loading were performed. Afterwards the beam was loaded until failure.

3. Test results

Failure of each beam was caused by the CFRP strip debonding from the concrete surface, induced by the intermediate crack debonding (ICD) developing to one of the supports. Depending on the anchorage system, failure resulted in the CFRP sliding from the anchorage plate or total CFRP debonding along the total length (Figure 4). The beam P7 failed due to debonding starting at the end of the CFRP prestressing section and propagating in both directions, to the support and to the midspan. After CFRP debonding, the fishbone-shaped crack layout in a bottom concrete cover was observed (Figure 4c).

Figure 4. View of bottom side after beam failure a) active, b) non-active anchorage, c) without anchorage system.

Independently from the CFRP anchorage system and the beam’s preloading level during application of the strip, CFRP debonding occurred when the strain increase in the CFRP strip reached value in the range from 6.4 to 9.3‰ (see Table 1).

CFRP debonding is clearly shown on the load - CFRP strain curve (Figure 5), that shows the total CFRP strain as a sum of prestressing and the test strain registered at the beam’s failure (\( \epsilon_{fp} + \epsilon_{f,\text{test}} \)). Under preloading of the beam P4 due to its dead load of 2F_p=26kN, the CFRP prestressing strain reaches value of 4.75‰.

Debonding starts under the external load of 2F=48kN (“A”) and propagates toward one of the supports (“B”). Shortly after this debonding, the opposite CFRP strip end debonding occurs under the same loading of 2F=48kN (“C”). At the moment, where the CFRP strip debonded at its full length and it was held only at the anchorage plates, it behaved as the external tension bowstring, until sliding of the CFRP end from the anchorage system (Figure 5).
4. Test results analysis

A summary of the ultimate loads, CFRP strains, corresponding stresses and the maximum CFRP strain registered in the test are shown in Table 1. The capacity of non-strengthened beam was calculated based on a non-linear model of reinforced concrete members [11]. The main assumptions of the model are as follows: non-linear strength-strain relationship for concrete in compression and tension (Figure 6a), experimental stress-strain relationships for reinforcing steel (Figure 6b), tension stiffening principle and the plane section principle. External load value is calculated based on the equilibrium condition of generalized forces in the cross-section (Figure 6c). The load for which a limit in strain in one of the materials is reached (\(\varepsilon_{cu}\) - in concrete of 3.5\% or \(\varepsilon_{su}\) - in steel) is accepted as the load bearing capacity of the reinforced concrete cross-section. The model has been successfully applied for the analytical verification of the load-strain and load-deflection relationship of the large number of RC members [1].

Figure 5. Strain of CFRP strips at the following load levels

Figure 6. Calculated model assumptions: stress-strain characteristic of a) concrete, b) steel and c) RC cross-section
Table 1. Summary of the test results

<table>
<thead>
<tr>
<th>Beam</th>
<th>$2F_p$ (kN)</th>
<th>$2F_p/2F_{u0}$ (-)</th>
<th>$2F_u$ (kN)</th>
<th>$2F_u/2F_{u0}$ (-)</th>
<th>$\eta$ (%)</th>
<th>$\sigma_\nu$ (MPa)</th>
<th>$\varepsilon_{\text{f,test}}$ (‰)</th>
<th>$\eta_\varepsilon$ (-)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3</td>
<td>6.1</td>
<td>0.25</td>
<td>52.6</td>
<td>2.19</td>
<td>5.20</td>
<td>913 (0.31 f_u)</td>
<td>9.30</td>
<td>0.87</td>
<td>CFRP debonding and end slipping from anchorage system</td>
</tr>
<tr>
<td>P4</td>
<td>19.8</td>
<td>0.76</td>
<td>48.3</td>
<td>1.86</td>
<td>4.75</td>
<td>834 (0.28 f_u)</td>
<td>6.85</td>
<td>0.69</td>
<td>CFRP debonding and end slipping from anchorage system</td>
</tr>
<tr>
<td>P7</td>
<td>6.1</td>
<td>0.23</td>
<td>50.4</td>
<td>1.92</td>
<td>5.10</td>
<td>885 (0.33 f_u)</td>
<td>6.40</td>
<td>0.68</td>
<td>CFRP debonding</td>
</tr>
</tbody>
</table>

$F_p$ - preloading at strengthening process
$F_{u0}$ - ultimate load of reference beam (cal.), $2F_{u0} = 24.0$kN (for P3), 26.0kN (for P4 and P7)
$F_u$ - ultimate load of strengthened beam (test)
$\eta$ - strength of prestressed CFRP strip
$\sigma_\nu$ - ultimate strength of CFRP (test), $f_u = 2970$MPa (for P3 and P4), 2695MPa (for P7)
$\varepsilon_{\text{f,test}}$ - CFRP strain increase (registered in the test for full range loading)
$\eta_\varepsilon$ - CFRP strain efficiency, $\eta_\varepsilon = (\varepsilon_f + \varepsilon_{\text{f,test}})/\varepsilon_f$

Strengthening ratio defined as the ratio of the ultimate load of the strengthened beam to the calculated ultimate load of the non-strengthened beam ($2F_u / 2F_{u0}$) varied from 1.86 for the beam P4 (strengthened under preloading of 0.76 F_u0 with the CFRP prestressed to strain $\varepsilon_{f0}=4.75%\varepsilon_f$) to 2.19 for the beam P3 (strengthened under dead load equal to 0.25 F_u0 with the CFRP prestressed to strain $\varepsilon_{f0}=5.20%\varepsilon_f$).

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**Figure 7. Average concrete tensile strain in a function of load.**

The influence of the CFRP prestressing on the stiffness and the ultimate load of the tested members is shown as a function of the average tensile concrete strain and the load (Figure 7). All tested members had similar stiffness after yielding of the longitudinal steel reinforcement. Vertical displacements of the beam P4 before rebar yielding were only 15% higher compared to displacement of beams strengthened under dead load.
The beam P4 showed a minor loss of the stiffness and the load capacity compared to the beams P3 and P7 strengthened under only dead load. The aim of the CFRP strips prestressing was to improve the serviceability state (deflections and crack width). Comparison of the deflection-load (v-2F) curves (Figure 8) shows that strengthening beam P4 with prestressed CFRP resulted in a significant reduction of the vertical displacement caused by the preliminary loading. The curves (v-2F) confirm high influence of the CFRP prestressing on the stiffness of the beam, especially in case of the beams P3 and P4, strengthened with the CFRP strips prestressed to the strains of 5.2‰ and 4.75‰, respectively (Table 1).

The test showed that even high beam preloading equal 0.76F₀ caused no significant loss of stiffness before and after steel yielding (Figure 8). High beam preloading caused only minor loss of the load capacity. The load-deflection curve inclinations are very similar (after preliminary loading) for all tested members, both before and after steel yielding. It confirms high efficiency of strengthening reinforced concrete members with prestressed CFRP strips. Despite very high exhaustion of the beams (far over the serviceability limit state and even ultimate limit state), application of the prestressed CFRP strip resulted in significant reduction of deflections, strains and the stiffness increase similar to non-preliminary-loaded beam.

The beam P3 showed the highest strengthening ratio (2F_u / 2F₀ = 2.19) and the maximum CFRP strain reached equal to 0.82ε₅₅.

![Figure 8. Midspan deflection of the beams P3, P4 and P7.](image)

5. Conclusions

The analysis of experimental test results of the RC beams strengthened in flexure with prestressed CFRP strips can be summarized with the following conclusions:
- High efficiency of described strengthening technique is confirmed by the strengthening ratio in a range of 1.9 to 2.2 of the non-strengthened beam’s ultimate load, while non-active CFRP strengthening increases the load capacity only from 1.4 to 1.5.
- Strengthening with pretension CFRP strips is the only alternative for highly exhausted members requiring retrofitting, where the passive strengthening would not prove satisfying results.
- The bond loss between composite and concrete, propagating to one of the supports was the most common failure mode.
- Strengthening of RC members with prestressed CFRP strips resulted in significant improvement of both ultimate limit state and serviceability limit state, especially for highly preloaded elements.
6. References


