The influence of the yield strength of the longitudinal reinforcement on the bending capacity of beams reinforced with CFRP strips

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ABSTRACT

Effective application of FRP laminates to concrete is possible only with proper understanding of physical phenomena accompanying of failure mechanisms. The most probable failure mode of RC beams strengthened with externally bonded FRP systems is an intermediate crack-induced debonding. Better knowledge of this failure mode will lead to more accurate designing that have important influence on safety and cost. This paper describes laboratory test on flexural strengthening of reinforced concrete elements with CFRP strips attached to the tensile soffit of the beams. Four RC beams were made of concrete with low strength of about 20 MPa with longitudinal reinforcement made with different types of steel and tested to failure in four-point flexure. Theoretical yield strength of steel reinforcement varied from 350 MPa to 1860 MPa but the reinforcement ratio remained almost constant at about 0.75%. All the beams had shear ratio about 3 and the same transverse reinforcement. All the beam failed due the intermediate crack-induced debonding or concrete crushing. At the failure, different strains and tensile stress were reached depending on the steel properties used as the longitudinal reinforcement. It was concluded that the important influence on the level of the FRP strips’ strain at collapse have the yield strength of applied reinforcement. With the increase of the yield strength of steel raised ultimate force and the strain in the tape at the delamination. For high strength steels damage occurred as a result of crushing concrete and thus delamination of the strip.

KEYWORDS

RC beam, strengthening, reinforcing, CFRP strips, steel yield strength, debonding.

INTRODUCTION

Using of fibre reinforced polymer (FRP) composites has become a popular technique for strengthening concrete structures. One of the most commonly used systems is external bonding of FRP strips or sheets directly to the tension face of beams or plates to increase the flexural strength of the member. This solution is easy to use, however, must be designed to avoid sudden failure due to composite delamination or debonding from the concrete surface. Based on years of research, some of which were first studied for concrete structures strength with mild steel plates and then with fibre reinforced polymer composites, different types failure modes have been noticed. These typical failure modes (Teng et al. 2003) are known as: flexural failure by compressive concrete crushing, flexural failure by FRP rupture, shear failure and interfacial debonding failure. According to Smith and Teng (2002), Teng et al. (2002), Oehler et al. (2003) Teng et al. (2004), Esfahani et al. (2007) interfacial debonding may occur through concrete cover separation, plate-end interfacial separation, intermediate flexural crack or intermediate flexural-shear crack debonding and critical diagonal crack induced interfacial debonding. Several analytical and empirical models for interfacial debonding were developed recently. All the calculations made in accordance for example with fib Bulletin 14 (2001), Teng et al. (2003) ACI 440.2R-08 (2008), Wu and Niu (2007), Sayed-Ahmed et al. (2009), leads to a reduction allowable strain or stress in the FRP laminate to prevent delamination. The calculation analysis of the elements strengthened in flexure takes into considerations many parameters associated with the RC element as well as the FRP laminates. These parameters are related to the geometry of the element, the strength of the concrete, the reinforcement ratio, the tensile modulus of elasticity of FRP, the rigidity of the attached material (thickness and number of layers) and the ratio between the element width to strip width. These calculation parameters omit yield strength of the applied reinforcement. In order to see if such an assumption is correct a research programme was prepared analyzing the influence of applying different kinds of steel on the bearing capacity of the element after strengthened. The aim of the study presented in this paper was to obtain a better knowledge of IC debonding RC structures strengthened with CFRP strips.
RESEARCH PROGRAMME

Specimens

While designing the test element it was assumed that it should collapse in maximum moment region through the concrete crushing in the compression or tape debonding under simultaneous big shear stress in the support region. A single-span, simple supported beam of 3,0 m length in four point flexure with two concentrated forces applied 1,0m from the supports creating pure bending region of 1,0 m length was chosen – Figure 1.

![Figure 1. Research element – geometry, basic and strengthening reinforcement](image)

The beams had a rectangular cross-section of 0,15×0,30 m and the effective depth $d = 0,27$m. Such a combination of the element dimensions caused the shear ratio to remain about 3, which allowed the observation of the influence of the shear stress without the dominance of this parameter on the ultimate load capacity of the element. It was decided that the research elements would be made of concrete of cube strength $f_{ck} = 20$MPa, so that the shear crack could appear in the early phase of the loading. In all element longitudinal reinforcement had almost constant ratio 0,75%. The yield strength of the steel used for the reinforcement was chosen as the variable parameter. In the research there were four types of steel used – deformed bar as well as prestressing strands with theoretical yield strength of $f_{yk} = 350, 410, 500$ and $1860$MPa. The main reinforcement consisted of correspondingly two bars $\varnothing 14$($A_{s,tot} = 3,08cm^2$) or three tendons of $\varnothing 12,5$mm ($A_{s,tot} = 2,79cm^2$) in tension and two deformed bars $\varnothing 12$mm in compression. The strengthening of the beams was made with the use of one CFRP strip S512 of $A_f = 60$mm$^2$, $b_t = 50$mm, $t_f = 1,2$mm, $E_f = 165$GPa [5] attached axially to the beam soffit. Real parameters of reinforcing steel strength obtained in the tensile test are given in Figure 2

![Figure 2. Real parameters of reinforcing steel strength](image)

Measurements

The measurements of the deformations were conducted with the use of a resistance strain gauges attached to the CFRP tape – Figure 3. Additionally the deformations on the surface of the concrete were measured with the use of inductive sensors attached along the lower and upper edge of the beam. – Figure 4.

![Figure 3. Strength – strain characteristics deformed bars reinforcement](image)
ANALYSIS OF THE RESEARCH

All the elements were made independently in different periods and they underwent the tests at a different time in relation to the moment production. The basic strength parameters of the applied materials and the ultimate forces are presented in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Age (days)</th>
<th>$f_y$ (MPa)</th>
<th>$A_{c_lig}$ (cm$^2$)</th>
<th>$f_{c, cube}$ (MPa)</th>
<th>$P_u$ (kN)</th>
<th>$\varepsilon_{fu}$ (%)</th>
<th>$\varepsilon_{cu}$ (%)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW 1</td>
<td>607</td>
<td>360</td>
<td>3.14</td>
<td>23.0</td>
<td>38</td>
<td>4.8</td>
<td>1.23</td>
<td>ICD</td>
</tr>
<tr>
<td>BW 2</td>
<td>590</td>
<td>430</td>
<td>3.18</td>
<td>24.0</td>
<td>47</td>
<td>5.2</td>
<td>1.53</td>
<td>ICD</td>
</tr>
<tr>
<td>BW 3</td>
<td>720</td>
<td>520</td>
<td>3.08</td>
<td>20.0</td>
<td>63</td>
<td>5.7</td>
<td>2.33</td>
<td>ICD</td>
</tr>
<tr>
<td>BW 4</td>
<td>1260</td>
<td>1860$^*$</td>
<td>2.97$^*$</td>
<td>17.6</td>
<td>75</td>
<td>6.5</td>
<td>3.77</td>
<td>CC/ICD</td>
</tr>
</tbody>
</table>

1) according to the producer’s data
ICD – debonding of the tape, CC – crushing of the concrete in the compression region

In all the elements at the load of 20 ÷ 30kN the shear cracks appeared in the support region. With the load increase the cracking appeared at the CFRP tape cut end off – Figure 4. However, these cracks did not cause the bearing capacity to deplete as a result of the debonding of the composite endings related to the shear crack.

The relationships between load and deflection at the centre of the span for all specimens are indicated in figure 5.
Figure 5. Applied load versus midspan displacement

Figure 6. Deformations of the CFRP tape along the element at different load levels
The beam BW4 with the strands as the reinforcement achieved the highest measured load value and of course the highest deflections. In all cases, the in midspan displacement the plastic deformation of the material is visible, for the beams BW1, BW2, BW3 it was related to the steel yielding and for the beam BW4 to the plastic deformation of concrete and, consequently in this case, concrete crushing.

The elements failed at different load levels as a result of CFRP tape delamination in the region of concentrated load application. At the moment of the delamination in compression region the smallest deformations of the concrete were observed in BW1 element ((εcu = 1,23‰), while the biggest in BW4 element (εcu = 3,77‰). In the latter case the concrete began to crush and delaminate in the compression region already under the load of about 67,5kN, and the delamination followed as a result of both the depletion of the bearing capacity of the compression region and the tape separating. The arrangement of the tensile strain along the tape under selected loads are presented in Figure 6. The deformation of the tape in the moment of delamination was different and equalled 4,8‰ in the case of BW1 element and 6,5‰ in the case of BW4 element.

The strength of the concrete had no substantial influence on the border deformation of the tape within the delamination process, as in the BW4 element with the biggest deformation concrete of the lowest strength parameter was used, i.e. fccube = 17MPa.

It should be assumed that should the element be made of concrete of higher strength, the deformation of the tape in the moment of debonding would have been even bigger. The comparison of the average deformations in the pure bending region in relation to the load level for all the elements are presented in Figure 7.

![Figure 7. Average deformations of CFRP tape within the pure bending area](image)

In the preliminary load phase the relation load - deformation of the tape is similar for all the elements – it is a linear relation. The differentiation begins when the reinforcement reaches the yield strength. Starting from this load level we can observe a definitely bigger increase of deformations in the tape. Only in the case of BW4 element the non-linear character of the deformation increase in the tape is connected with the strain of the compression region and the deformation of the concrete. In this case, the direct cause of the delamination of the element was the crushing of the concrete in the compression region.

It cannot be precisely estimated which tape deformations are followed by its delamination. They will depend on the parameters of the reinforcement steel used. It should be expected, however, that together with the increase of the concrete strength the adherence border stress tape-glue-concrete will be exceeded. Moreover, the separating of the tape in the beams reinforced with prestressing steel occur before the yielding of the reinforcement and potential crushing of the compression region. Because the steel applied in the research has a precise, as well as assumed yield strength, it is impossible to provide precise relation between the level of deformation of the reinforcement and the delaminating force causing the separating of the tape from the reinforced concrete beam.

**CONCLUSIONS**

The conducted research proved that the direct cause of the debonding of the tape may be related to the strength parameters of the longitudinal reinforcement of the beam. The yielding of the main reinforcement initiates the process of separating. The deformations of the tape in the delamination of the element are different, they depend on the yield strength of the reinforced steel applied and vary within range 4,8 – 5,7‰ for steel of fy = 360 – 520MPa and grow to 6,5‰ for steel of fyk = 1860MPa.
The strength of the concrete has a lower influence on the border deformations of the tape than the strength parameters of the steel when the concrete strength is of $f_{c,\text{cube}} \approx 20\text{MPa}$.

REFERENCES


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