THE LOAD-CARRYING CAPACITY OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CARBON FIBRE COMPOSITE IN THE TENSION ZONE SUBJECTED TO TEMPORARY OR SUSTAINED LOADING

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Abstract. The article presents the results of the research carried out on the reinforced concrete beams under bending strengthened in the tensile zone with carbon fibre composite. The beams under bending were subjected to short-term and sustained static loading. The duration of sustained loading was 400 and 863 days. A total of four series of beams with different reinforcement ratio and loading duration were tested. Experimental research showed that sustained loading reduces the load-carrying capacity of the beams. Prior to long-term testing of the beams, the load-carrying capacity of control beams subjected to short-term static loading was measured. The decrease of the strength of the beams was caused by a long-term creep effect of concrete in the compression zone as well as plastic shear deformations in the bond of concrete and carbon fibre. To calculate the bending capacity, the built-up bar theory enabling estimation of short and long-term deformation capacity in the bond of concrete and carbon fibre was applied.

Keywords: bending capacity, bond shear stiffness, long-term load, creep effect, distribution of deformations.

1. Introduction

Methods enabling calculation of the load-carrying capacity of a beam are based on the balance of resultant forces caused by internal effects and external actions. Therefore, two methods can be distinguished that are most frequently used: the method of balance of internal and external forces (An et al. 1991; GangaRao 1998; Toutanji 2006; Alagusundaramoorthy et al. 2003; Pham 2004; Lu 2007; Bencardino et al. 2007; Capozucca 2002) and the method based on the theory of built-up bars (Valivonis 2007; Marčiukaitis et al. 2007; Skuturna et al. 2008; Benyoucef et al. 2006, 2007).

If the first method is applied to determine the load-carrying capacity, according to ACI 440.2R-08 it is measured by creating balance of forces in respect to the weight centre of the compression zone cross-section (Fig 1):

\[ M_R = A_{sf} f_{sf} \left( d - \frac{\beta_1 x}{2} \right) + \psi_f A_f f_f \left( h - \frac{\beta_1 x}{2} \right). \]

(1)

If calculations are made according to Fib bulletin 14, the condition for balance of forces is:

\[ M_R = A_{sf} f_{sf} (d - \delta_{12} x) + A_f f_f (h - \delta_{12} x) + A_{s2} E_{s2} \left( \delta_{12} x - a_{12} \right). \]

(2)

where: \( A_f, A_{s1}, A_{s2} \) – the area of carbon fibre reinforcement, steel bar reinforcement in tension and compression; \( f_f, f_{sf} \) – strengths of carbon fibre and tensile steel reinforcement; \( x \) – the height of the compression zone; \( h \) – the height of strengthened beam; \( d \) – the effective depth of reinforced concrete beam; \( \delta_{12}, \delta_{12} \) – deformations carbon fibre composite and compressed steel reinforcement; \( E_f, E_{s2} \) – the modulus of carbon fibre composite and compressed steel reinforcement; \( \beta_1, \delta_1 \) – reduction coefficients of the compression zone \( \beta_1 = 0.65–0.85 \) and \( \delta_1 = 0.4 \).
The analyses of research related to the load-carrying capacity of flexural members shows that strengthened beams can fail in the compression zone, in the horizontal section by peeling off a strip of carbon fibre together with a layer of concrete or when carbon fibre composite rupture in the middle of the beam span when the limit stresses of carbon fibre composite are reached (Bulavs et al. 2005; Leung 2003; Maalej 2005; Marčiukaitis 2009; Ramos et al. 2006; Saxena et al. 2008; Thomsen et al. 2004). As research of other investigators shows, strengthened beams fail in the compression zone when the ratio of the width and height of the beam is close to 1 (Gao et al. 2007).

The bond of carbon fibre composite and concrete in strengthened structures is not stiff. When subjected to loading, due to shear deformations, the composite in the bond moves in respect to concrete. Due to this, the efficiency of strengthening reduces (Skuturna et al. 2008).

Therefore, the guide for the design ACI 440.2R-08 indicates that the force of carbon fibre composite is reduced by multiplying by coefficient $f = 0.85$.

$$M_0 = M_k + T_c \cdot a,$$  \hspace{1cm} (3)

where: $M_0$ – sum total of bending moments of separate members when the bond is stiff; $T_c$ – bond shear force is calculated according to the formula (Рожаницын 1986):

$$T_c = \frac{P \cdot a \cdot l_p}{\gamma_c} \left(1 - \frac{\sinh(\lambda \cdot l_p)}{\lambda \cdot l_p \cdot \cosh(\lambda \cdot 0.5l)} \right).$$  \hspace{1cm} (4)

The value $\lambda_c$ assessing the stiffness of the bond is calculated:

$$\lambda_c = \sqrt{\frac{\xi_c \cdot \gamma_c(t)}{E_c}} + \frac{1}{E_{eff} \cdot A_{eff}} + \frac{a^2}{E_{eff} \cdot I_{eff}},$$  \hspace{1cm} (5)

$$\xi_c(t) = \frac{b \cdot G_{eff}(t)}{a},$$  \hspace{1cm} (6)

$$G_{eff}(t) = \frac{110 + 2 \frac{E_c(t)}{E_{cm}} - \frac{4 \rho_{1s}}{\rho_{fe} \cdot 460 \cdot M_{c}}}{\rho_{fe} \cdot M_{k} \cdot k_n},$$  \hspace{1cm} (7)

where: $E_c(t)$ – the elasticity modulus of concrete is calculated according to EC2; $E_{cm}$ – the secant modulus of concrete; $\rho_{fe}$ – reinforcement ratio of carbon fibre composite; $\rho_{1s}$ – reinforcement ratio of steel reinforcement in tension zone; $M_{c}$ – the cracking moment; $M_k$ – the load-carrying capacity of the beams with external carbon fibre reinforcement when the bond between carbon fibre composite and concrete is stiff is calculated according to the formula 9; $k_n$ – coefficient which evaluates the type of anchorage of external reinforcement (when external reinforcement over supports $k_n=1$; when carbon fibre reinforcement is not additionally anchored).
\[ M_R = f_{cd} \cdot b \cdot x (d - 0.5 \cdot x) + E_f \cdot \epsilon_f \cdot A_f \cdot (d - a_{x2}) + A_f \cdot f_{cd} \cdot (d - a_{x2}). \]  
(9)

where: \( f_{cd} \) – strengths of concrete under compression; \( a_{x2} \) – distance to centroid of compressive steel reinforcement; \( a_f \) – distance to centroid of carbon fibre composite.

3. Specimens and methodology of the experimental research

4 series of beams were produced for experimental research. The project size of the samples was 100×200×1500 mm. The compression and tension zones of the first series of beams were reinforced with 2Ø6 reinforcing steel bars. The compression zone of the second series was reinforced with 2Ø6 reinforcing bars and the tension zone was reinforced with 2Ø8 reinforcing bars. The compression and tension zones of the third series of beams were respectively reinforced with 2Ø8 and 2Ø12 reinforcing steel bars. The compression zone of the fourth series of beams was reinforced with 2Ø6 reinforcing bars and the tension zone was reinforced with 2Ø14 reinforcing bars.

Carbon fibre of B8C and B12C series beams was glued up the supports. Carbon fibre in B6C and B14C series beams overlapped the supports. The cross-section area of carbon fibre reinforcement in all series of beams was the same.

Table 1. Material properties

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<th>( f_c ) (MPa)</th>
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<th>( f_t ) (MPa)</th>
<th>( E_t ) (GPa)</th>
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The characteristics of beam concrete, steel bars and composite carbon fibre reinforcement are given in Table 1.

Experimental research on the second series of beams was carried out under short-term loading. Beams of all other series were tested under both short-term and sustained loading.

The reinforced concrete beams were tested on the testing stand (Fig 4). The length of the beam span was 1200 mm. One hydraulic jack was used to create loading. The loading was increased by stages. The beam testing scheme is show in Fig 5.

Fig 4. Overview of test setup for short-term loading
During the testing the following measurements were made: beam deflection and displacement of carbon fibre composite in respect to concrete, deformations of the external carbon fibre reinforcement, deformations of concrete in the compression and tension zones, the cracking moment, the character and the width of the increase of cracks were also recorded.

For sustained bending of beams the equipment (Figs 6, 7) which ensured a stable level of loading during the whole period of the research was used. The places of concentrated forces were the same as in control beams. To achieve the effect of sustained loading the beams were loaded up to the level of 0.6\(M_R\) of the load-carrying capacity. During the testing, similarly as with beams under short-term loading, deformations and beam deflection were measured here. At the end of sustained testing the beams are unloaded and each sample is subjected to short-term loading until it reaches the capacity loading.

It has also been found out that carbon fibre reinforcement in the tension zone influences increase of cracks, limits the development of cracks, therefore, the width and height of cracks do not increase. Carbon fibre is glued to reinforced concrete beams with epoxy adhesive. When adhesive deforms, carbon fibre composite slips horizontally and causes stresses in concrete. Due to these stresses, additionally to vertical cracks, horizontal cracks appear in concrete (Fig 9). Research shows that these cracks interconnect and in separate zones damage the bond between carbon fibre composite and concrete. When the bond is damaged, increase in steel bar deformation significantly grows (Fig 8 refraction of the graph).

Later, depending on how carbon fibre composite was anchored, beams failed by peeling off carbon fibre composite (Fig 10) or carbon fibre rupture (Fig 11).

The research conducted shows that the load-carrying capacity of the strengthened beams subjected to short-term loading compared to the beams without external reinforcement increases. The load-carrying capacity of B6C series beams increases more than 3 times; the load-carrying capacity of B8C series beams increases more than 70\%; the load-carrying capacity of B12C series beams increases more than 50\% in comparison with the beams that were not strengthened (Table 3).
Experimental research revealed that the higher reinforcement ratio of steel bar reinforcing, the lower the strengthening effect of carbon fibre composite. The maximum strengthening effect is reached when steel bars reinforcement ratio is low. Experimental research showed that the best strengthening effect was reached in B6C beams since the strength qualities of concrete and composite were more used because higher deformations were reached (Figs 12, 13). Research also showed that when members are considerably reinforced, carbon fibre fixed in the tension zone is not fully used (Figs 12, 13).

The sustained bending tests revealed that the intensity of creep deformations in the compression zone of concrete is higher than in the tension zone. It has also been found out that under sustained loading deformations in the tension zone at the steel bar reinforcing level are bigger than the composite layer deformations (Figs 14, 15). This enables us to make a conclusion that the composite layer under tension displaces in respect to reinforced concrete beam. Therefore, when repeatedly loaded ultimate deformations at which the load-carrying capacity is lost are reached faster.

The intensity of deformations reached when loading was 0.6\(M_R\) depended on reinforcement ratio of steel bar reinforcing. When beams B 6.3C\(_1\) and B6.4C\(_1\) are loaded until the level of permanent load is reached, the steel reinforcement under tension reaches yield stresses. When beams are unloaded, residual deformations in the layers under tension are measured (Fig 16, Table 2).
Fig 15. Distribution of creep deformations in the layers under tension in the beam B14-3Ct: ε-1 composite layer under tension; ε-2 the layer with steel bar reinforcement under tension

Fig 16. Distribution of relative deformations in beam B6.3Ct: ε-1 composite layer under tension; ε-2 the layer with steel bar reinforcement under tension

Fig 17. Distribution of relative deformations in beam B12.3Ct: ε-1 composite layer under tension; ε-2 the layer with steel bar reinforcement under tension

Fig 18. Distribution of relative deformations in beam B14.3Ct: ε-1 composite layer under tension; ε-2 the layer with steel bar reinforcement under tension

Table 2. Creep and residual deformations of layers under tension

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<th>ε_{res,cs} \cdot 10^2</th>
<th>ε_{cr,f} \cdot 10^2</th>
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where: ε_{cr,cs}, ε_{res,cs} – creep and residual deformations of layer with steel bar reinforcement under tension; ε_{cr,f}, ε_{res,f} – creep and residual deformations of composite layer under tension.

Experimental research showed that the load-carrying capacity of beams after sustained loading decreased. The biggest decrease in load-carrying capacity was displayed in the beams which were the least reinforced and it reached up to 28%. The decrease of load-carrying capacity in the beams reinforced with Ø12 and Ø14 longitudinal reinforcement reached from 4% to 7%. This can be explained by creep deformations of concrete in the compression zone and shear creep deformations of carbon fibre composite under tension. When the strengthened beams are unloaded, residual deformations remain in the tensile and compressed layers. Deformations of specimens increase starting from the residual value when sustained loading test is over and beams are subjected to short-term loading. Deformations in the layers at each loading stage are bigger than in control beams at the same level of loading. Therefore, failure of beams subjected to sustained loading occurs earlier than that of the beams tested by applying only short-term loading. The results of the load-carrying capacity of the beams are presented in Table 3.

Calculation of the load-carrying capacity of strengthened beams under temporary and sustained loading was made according to the suggested methodology which evaluates the stiffness of bond of concrete and carbon fibre composite (Formula 8) as well as the influence of sustained loading. The results of calculation are given in Table 3.
Calculation results show that if the suggested calculation method is used, the load-carrying capacity of strengthened beams can be measured quite precisely. Analysis of results shows that calculation exactness mainly depends on reinforcement ratio. Calculations of load-carrying capacity of beams whose reinforcement ratio is very low or big are not so exact (1–38 %) than of beams where reinforcement ratio is normal (1–12 %).

Conclusions

Research showed that carbon fibre composite significantly increases the load-carrying capacity of strengthened members. The effect of strengthening depends on reinforcement ratio of steel bar reinforcement in the specimens. The lower the ratio of this reinforcement, the higher the strengthening effect since the strength of carbon fibre composite is better used. The higher reinforcement ratio of steel bar reinforcement, the lower the effect of strengthening.

It has been defined that sustained loading influences the load-carrying capacity of strengthened beams. Under sustained loading creep deformations of concrete in the compression zone as well as carbon fibre composite occur and they remain when specimens are unloaded. When beams are again subjected to short-term loading, deformations increase starting from the residual values. As a result, the load-carrying capacity of the specimens decreases in comparison with the load-carrying capacity of the beams loaded only short-term.

A calculation method that evaluates the stiffness of bond carbon fibre composite and concrete as well as the influence of sustained loading has been suggested. The load-carrying capacity calculation results quite precisely coincide with the experimental values.

References


