VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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INFLUENCE OF LONG-TERM LOAD ON THE BEHAVIOUR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CARBON FIBRE COMPOSITE

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
CIVIL ENGINEERING (02T)

VGTU
LEIDYKLA
Vilnius TECHNIKA 2010

Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2006–2010.

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The dissertation will be defended at the public meeting of the Council of Scientific Field of Civil Engineering in the Senate Hall of Vilnius Gediminas Technical University at 10 a. m. on 31 January 2011.

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The summary of the doctoral dissertation was distributed on 30 December 2010.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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ILGALAIKĖS APKROVOS ĮTAKA ANGLIES PLUOŠTU SUSTIPRINTŲ LENKIAMŲJŲ GELŽBETONINIŲ ELEMENTŲ ELGSENAI

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
STATYBOS INŽINERIJA (02T)

LEIDYKLA
Vilnius TECHNIKA 2010

Disertacija rengta 2006–2010 metais Vilniaus Gedimino technikos universitete.
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Disertacija bus ginama viešame Statybos inžinerijos mokslo krypties tarybos posėdyje 2011 m. sausio 31 d. 10 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.

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Disertacijos santrauka išsiuntinėta 2010 m. gruodžio 30 d.

Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).

VGTU leidyklos „Technika“ 1850-M mokslo literatūros knyga.

Introduction

Topicality of the problem. Carbon fibre reinforced polymer (CFRP) is widely applied in strengthening or retrofitting elements of damaged structures. Effective performance of strengthened structures improves perspective application of CFRP. The abundance of investigations of the elements strengthened with CFRP and the demand for design requirements prove a perspective usage of CFRP in the future. Technologies of strengthening with CFRP are developed in many countries.

Strengthening of the elements of structures with CFRP is generally performed by creating a lateral layer on the surface of the element of the structure. Interception of stresses in the element of a strengthened structure is the major purpose of a CFRP layer. Epoxy resin adhesives are used for anchoring the CFRP layer on the surface of the element of the structure. When a reinforced concrete element is strengthened, we can make an assumption that concrete is elastic plastic material. So, if concrete is the basis on which the CFRP layer is anchored, then shear stresses in the joint of concrete and carbon fibre composite (CFRP) undertake displacement between the layers. Experimental tests of concrete and carbon fibre composite (CFRP) interaction show that the joint between concrete ant the carbon fibre composite is not stiff. Therefore, an induced displacement between the layers influences the behaviour of reinforced concrete beams strengthened with CFRP.

A long-term load intensity and the duration of load are significant for reinforced concrete beams strengthened with CFRP. Naturally, creep deformations in concrete increase during a long-term loading. Consequently, shear creep deformations in the joint of concrete and carbon fibre composite (CFRP) increase. There are no experimental tests which can indicate the influence of CFRP layer displacement on the behaviour of a strengthened reinforced concrete beam. It is important to investigate the additional influence of CFRP layer anchoring during a long-term bending test.

Deflection calculation methods of reinforced concrete beams strengthened with CFRP where the section of the beam is estimated as solid can’t be used. Displacement between layers increases the increment of the deflection of beams. When strengthened beams are loaded with a long-term load, shear creep deformations in the joint of concrete and carbon fibre composite increase and the additional deflection increment increases too. Therefore, the calculation method based on built-up-bars theory should be proper for evaluating the displacement of layers. The calculation method based on the mentioned theory can estimate the alteration of the stiffness of the joint of concrete and carbon fibre composite during a long-term loading.

Topicality of the work. Effect of shear stresses in joint of concrete and carbon fibre composite decrease the stiffness of joint and composite layer slips in respect with concrete layer. Consequently load carrying capacity of strengthened beam decrease and deflection increase. So it is important to investigate behavior of strengthened beams under long-term load action, because shear creep deformations additionally reduces stiffness of concrete and carbon fiber composite joint.

Research object. The object of the research is the analysis of the performance of reinforced concrete beams under bending strengthened with carbon fibre reinforced polymer and subjected to a long-time static loading.

Main objective. The objective of this work is to accomplish experimental tests and determine a long-term load influence on the behaviour of strengthened reinforced concrete beams. It is pursued to apply the built up bars theory in calculation of the deflection and load carrying capacity of the beam strengthened with carbon fibre with estimation of the influence of a long-term load.

Main tasks

Following tasks formulated to reach the main objective:

1. Perform the analysis of accomplished experiments associated with strengthened reinforced concrete beams. Determine the influence of long-term load on the behaviour of strengthened beams. Discuss calculation methods that evaluate the influence of long-term load on the deflection and the load carrying capacity.
2. Accomplish experimental test. Observe the behaviour of strengthened beams under a long-term load effect. Investigate the evolution of the deformations of layers and beam deflections. Identify the load carrying capacity of strengthened beams after a long-term load effect.
3. Compare experimental results with the calculated ones with the help of a proposed methodology.
4. Perform analysis of experimental results and propose the most suitable method for additional carbon fibre composite anchorage.

Methodology of research. To perform experimental tests of the strengthened beams loaded with a long-term static loading. Reinforced concrete beams are strengthened with carbon fibres reinforced polymer (CFRP) in the tensioned external layer. Calculation of the deflections of beams and the load carrying capacity under a long-term load action is performed with the help of the built up bars theory. According to this theory, the degradation of the stiffness of concrete and CFRP joint in time is evaluated.

Scientific novelty

1. The confinement of a tensioned concrete zone with CFRP for bending stiffness was evaluated during long-term loading.
2. Experimentally investigated and theoretically evaluated joint stiffness of a tensioned concrete and carbon fibre composite during long-term loading.
3. It was experimentally verified that the influence of a long-term load significantly increases displacement of the carbon fibre composite layer. It is proved that displacement of a carbon fibre composite layer increased the deflection increment of a strengthened beam during load term loading. This effect reduced the load carrying capacity of a strengthened beam after a long-term load influence.
4. A deflection calculation method for strengthened reinforced concrete beams with carbon fibre composite was proposed. The calculation method estimates the alteration of concrete and carbon fibre composite joint stiffness during a long term loading.
5. The calculation method of the load carrying capacity of strengthened reinforced concrete beams with carbon fibre composite estimates the alteration of concrete and carbon fibre composite joint stiffness. This allowed decreasing the load carrying capacity after a long-term load action.

Practical value. The influence of shear creep deformations on the deflections and the load carrying capacity of strengthened reinforced concrete beams were determined. Experimental test showed that it is important to evaluate the evolution of shear creep deformations in concrete and carbon fibre composite joint. The proposed calculation method for a strengthened reinforced concrete beam deflection and the load carrying capacity estimates the alteration of concrete and carbon fibre composite joint stiffness. It is important to use additional anchoring of carbon fibre composite layers in order to decrease the alteration of stiffness and the increment of deflection when a beam is subjected to a long-term load action.

Defended propositions

1. A calculation methodology of deflections and the load carrying capacity of reinforced concrete beams strengthened with carbon fibre reinforced polymer was proposed. This methodology evaluates the degradation of the stiffness of a concrete and CFRP joint under a long-term load effect.
2. The analysis of experimental results showed that the effect of a long-term load induces shear creep deformations in a concrete and CFRP joint. This effect has a negative influence because it reduces the load carrying capacity of strengthened beams.
3. An additional anchoring of a carbon fibre composite layer is the right way to reduce the evolution of deflections and save the load carrying capacity of

strengthened beams. Additional anchoring of a carbon fibre composite layer reduced deflection from 1,14 to 1,97 times.

The scope of the scientific work. The thesis consists of an introduction, four main chapters, the results and conclusions and a list of used literature. This work consists of 79 pictures, 13 tables; 115 list of references. The total scope of dissertation is 150 pages.

1. Review of experimental researches and calculation methods of ferroconcrete beams strengthened with carbon fiber composite in the tensioned zone

The first chapter reviews the appliance of carbon fibre composite polymer in strengthening of structures. The influence of a long-term load on concrete, polymer matrix, carbon fibre reinforced composite and strengthened concrete beams is also considered. Calculation methods that evaluate the influence of a long-term load on the strengthened reinforced concrete beam deflection were also considered.

The accomplished analysis of concrete subjected to compression and tension under a long-term action showed that concrete compressive and tensile strength can decrease. According to the degradation of concrete strength, concrete and carbon fibre composite joint stiffness must decrease too.

Short-term load experimental tests with strengthened beams showed that the carbon fibre composite layer slips respectively with a reinforced concrete beam. This means that concrete and carbon fibre joint is not stiff. Respectively, with a long-term load action the displacement between reinforced concrete and the carbon fibre composite layer must increase.

The long-term load intensity when a beam is strengthened is a significant factor for the strengthened beam deflection increment and the load carrying capacity. The review of the behaviour of strengthened reinforced concrete beams with a carbon fibre composite showed that there are not sufficient experimental tests which could reveal the influence of the slip of the carbon composite layer on the behaviour of the strengthened beam under a long-term load.

Calculation methods of strengthened reinforced concrete beams for deflections and the load carrying capacity generally are based on the internal and external force balance. So, these methods normally cannot estimate the joint stiffness of concrete and carbon fibber composite without any reduction coefficient of the carbon fibre composite layer.

2. Evaluation of a long-term load influence on the ferroconcrete beams

Many researchers have established that the joint of concrete and CFRP under a short-term loading is not stiff because the CFRP layer slips in the horizontal direction due to shear stresses action. The horizontal slip caused by a short-term loading decreases the bending moment capacity. A long-term loading generates creep deformations induced by shear stresses in the concrete and CFRP joint. Respectively, the increment of deflection increases. The influence of creep deformations induced by shear stresses on the bending moment capacity and the increment of deflection is underestimated in design recommendations ACI 440.2R-02 and FIB bulletin 14. Methodologies for calculation of the load carrying capacity and deflections proposed by other researchers mostly evaluated only the increment of concrete creep deformations in the compressed section zone, whereas the load carrying capacity of a tensioned CFRP element was decreased by a reduction coefficient. The stiffness of the concrete ant CFRP joint can be estimated by applying Ржаницын (1986) built-up bars theory. Application of this methodology can estimate the evolution of shear creep deformations and the degradation of concrete and composite joint stiffness.

The load scheme of a strengthened beam is presented in Fig. 1. A considered beam section is divided into separate elements (Fig. 2): 1 – reinforced concrete element; 2 – CFRP element. Then the beam is subjected to bending when shear stresses between reinforced concrete and CFRP element initiate. These shear stresses initiate shear deformations and respectively displacements of each element rise. The displacement of a reinforced concrete element can be noted as u_c and the displacement of CFRP can be noted as u_f. Since the concrete and CFRP joint is not stiff, the difference between displacements of each element will be a slip:

$$u_l = u_f - u_c. \tag{1}$$

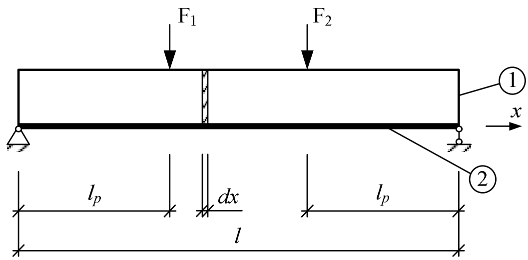

Fig. 1. Loading scheme of strengthened reinforced concrete beam

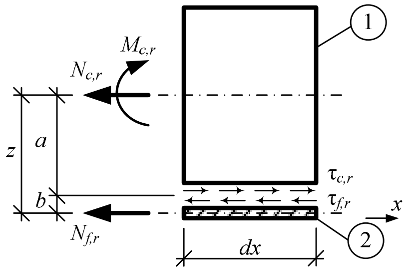

Fig. 2. Reinforced concrete beam *dx* length divided into separate elements. Here 1 – reinforced concrete element; 2 – CFRP element

According to the shear stresses effect, the evolution of creep deformations in the joint starts and displacement between reinforced concrete and carbon fibre composite element increases (Fig. 3). The short-term and long-term load induced displacement increments consisting of parts of elastic and plastic deformations (Fig. 3).

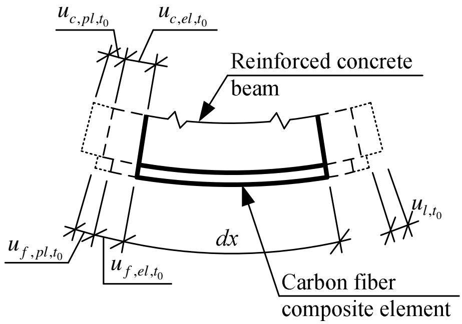

Fig. 3. Displacement between separate elements due to the evolution of creep deformations in a joint of CFRP and concrete

According to the built up bar theory, a stiff joint between a reinforced concrete element and a CFRP element was neglected and additionally shear forces were added. Then there is a rule that displacement between elements induced by external axial and bending moment forces as well as internal added shear forces must be equal zero. Then a major equation looks as follows:

$$\Delta_{N,M} + \Delta_k T_k = 0. \tag{2}$$

Here $\Delta_{N,M}$ – displacement induced by the external forces effect in a released way between separate elements: Δ_k – displacement induced by the unitary shear forces effect in a released way between separate elements. The influence of shear forces during a long-term loading period on the alteration of joint stiffness can be expressed as follows:

$$\Delta_k(t) = \gamma_{t_0,t_1} = \frac{1}{E_{c,eff,t_0} \cdot A_{c,eff,t_1}} + \frac{\varphi_{c,t_0}}{2 \cdot E_{c,eff,t_0} \cdot A_{c,eff,t_0}} + \frac{\varphi_{c,t_1}}{2 \cdot E_{c,eff,t_0} \cdot A_{c,eff,t_1}} + \frac{a^2}{E_{c,eff,t_0} \cdot I_{c,eff,t_1}} + \frac{a^2 \cdot \varphi_{c,t_0}}{2 \cdot E_{c,eff,t_0} \cdot I_{c,eff,t_0}} + \frac{a^2 \cdot \varphi_{c,t_1}}{E_{c,eff,t_0} \cdot I_{c,eff,t_1}} + \frac{1}{E_{f,t_0} \cdot A_{f,t_1}} + \frac{\varphi_{c,t_0}}{2 \cdot E_{f,t_0} \cdot A_{f,t_0}} + \frac{\varphi_{c,t_1}}{2 \cdot E_{f,t_0} \cdot A_{f,t_1}}. \quad (3)$$

Formula 3 is proper for concrete when 28 days of hardening are reached. For a longer concrete hardening period this expression is:

$$\gamma_{t_0;t_1} = \frac{k_1}{E_{c,eff,t_0} \cdot A_{c,eff,t_0}} + \frac{k_2}{E_{c,eff,t_0} \cdot A_{c,eff,t_1}} + \frac{k_1 \cdot a^2}{E_{c,eff,t_0} \cdot I_{c,eff,t_0}} + \frac{k_2 \cdot a^2}{E_{c,eff,t_0} \cdot I_{c,eff,t_1}} + \frac{k_1}{E_{f,eff,t_0} \cdot A_{f,eff,t_0}} + \frac{k_2}{E_{f,eff,t_0} \cdot A_{f,eff,t_1}}. \quad (4)$$

The parameter which evaluates the alteration of joint stiffness:

$$\lambda(t) = \sqrt{\xi_k(t) \cdot \gamma(t)}. \quad (5)$$

Here $\gamma(t)$ parameter is evaluated by 3 and 4 formulas according to appropriate loading conditions.

General stiffness of the interaction of separate elements

$$\xi_k(t) = \frac{b \cdot G_{c,eff}(t)}{a(t)}. \quad (6)$$

Here $G_{c,eff}(t)$ – effective shear modulus.

$$G_{c,eff}(t) = 0{,}00234 E_c(t) + 8{,}31 \frac{\mu_{s1}}{\mu_f} + 11{,}04 \frac{M_e}{k_a \cdot M_s}, \text{ [MPa]}. \quad (7)$$

Here $E_c(t)$ – concrete modulus of elasticity [GPa] at different loading time periods can be calculated by an adjusted effective modulus method; μ_{s1} – reinforcement with steel ratio in a tensioned section; μ_f – reinforcement with carbon fibre composite ratio; M_e – effective bending moment; M_s – load carrying capacity of non-strengthened reinforced concrete beams; k_a – coefficient which evaluates the method for additional anchoring of a carbon fibre composite layer.

According to the built-up-bars theory, the deflection of a strengthened beam loaded with evenly distributed load:

$$\omega(t)=p\left(\frac{l^4}{32E_{eff}(t)\cdot I_{eff}(t)}+\frac{l^2}{4D(t)}\left(\frac{ch(0{,}5\cdot\lambda(t)\cdot l)-1}{\lambda(t)^2\cdot ch(0{,}5\cdot\lambda(t)\cdot l)}\right)\right). \qquad (8)$$

Deflection of a strengthened beam consisted of two separate elements and was loaded with two concentrated loads (Fig. 1):

$$\omega(t)=M_e\left(\frac{l^2}{8E_{eff}(t)\cdot I_{eff}(t)}+\frac{1}{D(t)}\left(\frac{ch(0{,}5\cdot\lambda(t)\cdot l)-1}{\lambda(t)^2\cdot ch(0{,}5\cdot\lambda(t)\cdot l)}\right)\right). \qquad (9)$$

Here $E_{eff}(t)\cdot I_{eff}(t)$ – effective bending stiffness. If a long-term load influence is not estimated:

$$E_{eff}I_{eff}=\left(E_{c,eff}I_{c,eff}+E_fI_f\right)\cdot\frac{E_{c,eff}A_{c,eff}\cdot E_fA_f\cdot a^2}{E_{c,eff}A_{c,eff}+E_fA_f}. \qquad (10)$$

When a long-term load influence is estimated, the effective bending stiffness:

$$E_{eff}(t)I_{eff}(t)=\frac{B_1(t)+B_2(t)+B_3(t)}{B_4}\cdot\frac{E_{c,eff,t}{}^2}{\left(E_{c,eff,t}\cdot A_{c,eff,t}+E_f\cdot A_f\right)}. \qquad (11)$$

If a beam is strengthened and loaded after more than 28 days of concrete hardening, then the effective bending stiffness:

$$E_{eff}(t)I_{eff}(t)=\frac{B_{1,t}(t)+B_{2,t}(t)}{B_3}\cdot\frac{E_{c,eff,t}{}^2}{\left(E_{c,eff,t}\cdot A_{c,eff,t}+E_f\cdot A_f\right)}. \qquad (12)$$

The beam is cracked longitudinally in pure bending zone. The section between vertical cracks is under the sway of tension and compression, so this part of the section will crack when it reaches ultimate tension stresses. Respectively, with an evolution of shear creep deformations in the joint of concrete and carbon fibre composite, the concrete layer between the tensioned steel reinforcement and the external CFRP layers undergoes the influence of shear cracking. Summarizing the contribution of each crack value to the bending stiffness it is important to estimate the restraint effect on the growth of the cracks provided by the CFRP layer. The estimation of the influence of cracks on the effective bending stiffness is presented in Fig. 4.

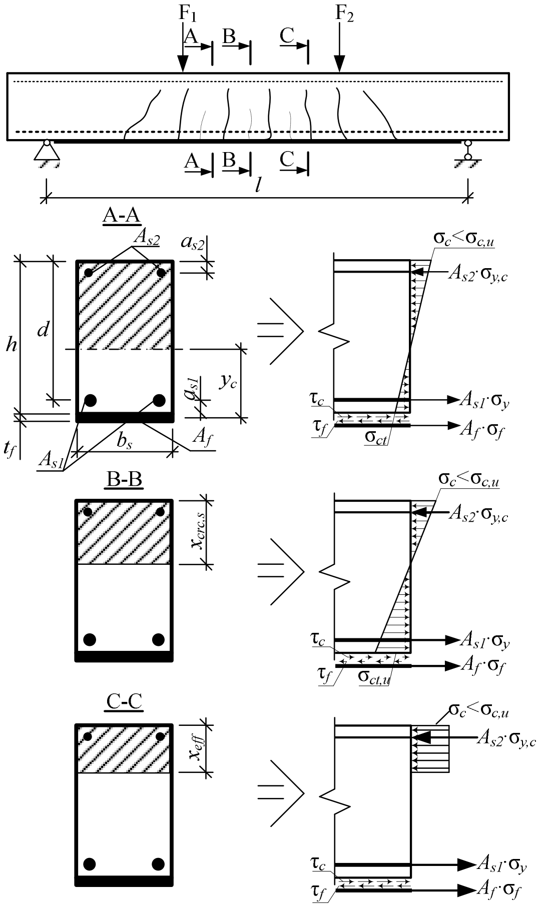

Fig. 4. Evaluation of a cracked beam sections for bending stiffness

So, the effective inertia moment of a cracked strengthened beam is proposed:

$$I_{c,eff}(t)=\left(\frac{M_{crc}}{M_e}\right)^3\cdot\beta_2(t)\cdot I_{gros}(t)+\left(\frac{M_{r,s}}{M_e}\right)^3\cdot\beta_1\cdot I_{crc}(t)-\left(\frac{M_{crc}}{M_e}\right)^3\cdot\beta_2(t)\cdot I_{crc}(t)+I_s(t)-\left(\frac{M_{r,s}}{M_e}\right)^3\beta_1\cdot I_s(t). \tag{13}$$

Here M_{crc} – the moment of cracking; $M_{r,s}$ – the ultimate moment of a non-strengthened beam; M_e – the ultimate moment of a strengthened beam; β_1 – coefficient: $\beta_1 = \frac{E_{fe} \cdot A_{fe}}{E_s \cdot A_{s1}}$; $\beta_2(t)$ – coefficient: $\beta_2(t) = \frac{A_f \cdot E_f}{x_{eff}(t) \cdot b_s \cdot E_c(t)}$; $I_{gros}(t)$ – the inertia moment of a non-cracked cross section (A-A); $I_{crc}(t)$ – the inertia moment of a cracked section (C-C); $I_s(t)$ – the inertia moment of a section with a newly opened crack (B-B).

The load carrying capacity of a strengthened beam after a long-term load action:

$$M_R = M_{r,c} + T_{c,k} \cdot a. \tag{14}$$

Here $M_{r,c}$ – the load carrying capacity of a reinforced concrete beam; $T_{c,k}$ – shear force in a joint of concrete and carbon fibre composite with evaluation of a long-term load action:

$$T_{c,k}(t) = \frac{F \cdot a}{\gamma(t) E_{c,eff}(t) I_{c,eff}(t)} \left[\frac{sh\lambda(t) \cdot l_p \cdot ch\lambda(t) \cdot (0{,}5l - x)}{\lambda(t) \cdot ch(\lambda(t) \cdot 0{,}5l)} - l_p \right]. \tag{15}$$

Here $\gamma(t)$ – parameter which evaluates the influence of shear forces during a long-term load period for a joint stiffness alteration can be calculated by formulas 3 and 4.

3. Experimental research of ferroconcrete beams strengthened with carbon fibre composite

33 reinforced concrete beams were prepared for experimental tests. The projected dimensions of beams were 100×200×1500. The beams were divided into three groups according to the ratio of their reinforcement with tensioned steel. First group beams in the tensioned and compressed section zones were reinforced with 2Ø6 steel bars ($\mu_s = 0{,}388\ \%$). Second group beams in the tensioned section zone were reinforced with 2Ø12 steel bars ($\mu_s = 1{,}29\ \%$) and in the compressed section zone with 2Ø8. Beams of the third group respectively were reinforced with 2Ø14 ($\mu_s = 1{,}76\ \%$) and 2Ø6 steel bars. Carbon fibre tape of 100 mm width was used for strengthening. The tensioning strength of the carbon fibre tape: $f_{f,t} = 1988\ \text{MPa}$. Modulus of elasticity: $E_{f,t} = 230\ \text{GPa}$. Cross section area: $A_{f,t} = 0{,}1837\ \text{cm}^2$. The load carrying capacity of control

strengthened and not strengthened beams were determined before the long-term load experiment.

It was experimentally determined that an unexpected increase of deformations after 150 days of a long-term load action can occur in the tensioned layer with a steel bar (Fig. 5). Deformations in the layer with a tensioned steel bar increase faster than in the external layer of a carbon fibre composite. An unexpected increase of deformations increment decreases after 125 days. For beams with reinforcement ratio $\mu_s = 0{,}388~\%$, at this period deformations in the layer with a steel bar were approximately 10,5 time higher than in the external layer with a carbon fibre composite.

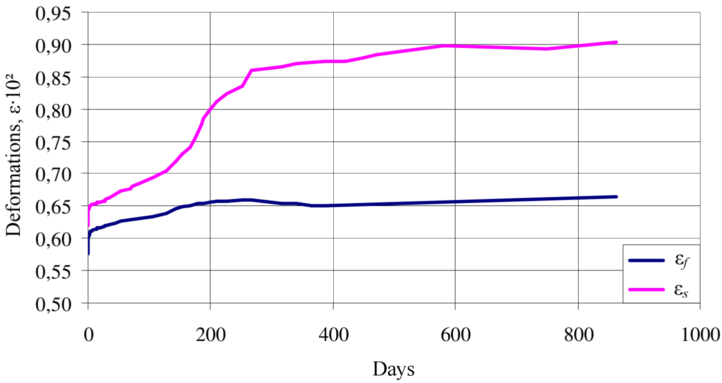

Fig. 5. Evolution of deformations in tensioned layers under a long-term loading of the beam I.B6.5Ct. ε_f – layer of a tensioned CFRP element; ε_s – concrete layer with a tensioned steel bar

There is also an increasing tendency of deformation increment in a tensioned layer with a steel bar in beams with reinforcement ratio $\mu_s = 1{,}29~\%$. After 110 days of a long-term load action, deformation increment in the layer with a steel bar was approximately 2,6 times higher than in the external layer with a carbon fibre composite.

Deformations in the tensioned layer with a steel bar of strengthened beams, where reinforcement ratio $\mu_s = 1{,}76~\%$, increase faster after 150 days of a long-term load action and decelerate after 125 days. During this period deformations in the tensioned layer with a steel bar increased up to 6 times faster than in the external layer with a carbon fibre composite.

Increase of deformations in the tensioned layer with a steel bar occurs because the stiffness of the concrete and carbon fibre joint decreases due to the action of shear stresses in the joint. During a long-term load action, shear stresses reduce concrete resistance because micro cracking of concrete in a joint proceeds and micro cracks join. So, the anchoring foundation of a carbon fibre composite becomes weaker and the composite layer slips in respect to concrete.

It was experimentally determined that displacement of the carbon fibre composite layer influenced the deflection increment in strengthened beams. Deflection increment of beams where reinforcement ratio $\mu_s = 0{,}388\ \%$ started increasing at the same time when displacement increase of the external composite layer started (Fig. 6. curves I.B6.5Ct and I.B6.6Ct). Increases of deflection increment of beams where reinforcement ratio $\mu_s = 1{,}29\ \%$ were not observed because displacement in comparison with the beams in other groups is smaller. Deflection increment of beams where reinforcement ratio $\mu_s = 1{,}76\ \%$ at the moment when displacement started to increase was constant till displacement of the external layer decreased.

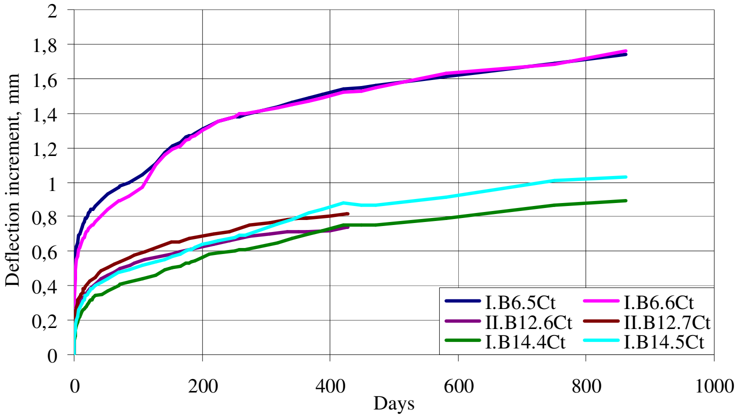

Fig. 6. Evolution of deflection increment under a long-term loading in beams I.B6.5Ct; I.B6.6Ct; II.B12.6Ct; II.B12.7Ct; I.B14.4Ct; I.B14.5Ct

It was experimentally determined that additional anchoring of the external composite layer reduces decrease of the stiffness of the concrete and carbon fibre composite joint. Therefore, the deflection increment of strengthened beams during a long-term load action decreases in comparison with the beams where the external composite layer is not additionally anchored. When the external composite layer was additionally anchored with carbon fibre clamps, the deflection increment during 100 days of a long-term load action was 2,1 times lower than the deflection increment of strengthened beams without an additionally anchored external composite layer. When the external composite layer is additionally anchored with steel clamps or a pressed steel plate, the deflection increment during 100 days of a long-term load action respectively was 1,77 and 1,19 times lower than the deflection increment of strengthened beams without an additionally anchored external composite layer.

Different long-term load intensity influenced the stiffness decrease in the concrete and carbon fibre composite joint. When long-term load intensity reaches 78 % of the load carrying capacity of the control beams, displacement of the external composite layer is 10,6; 3,4 and 1,5 times bigger than that of the strengthened beams where long-term load intensity respectively reached 43 %, 58 %, 62 % of the load carrying capacity of the control beams.

When the external composite layer is additionally anchored with carbon fibre clamps, the displacement increment during 50 days of a long-term load action was 12,5 times lower than the displacement increment of the strengthened beams without an additionally anchored external composite layer. Also 7,4 and 5,2 times lower when the external composite layer respectively was anchored with steel clamps or a pressed steel plate.

It was experimentally determined that after elimination of a long-term load, displacement between layers remained. The highest long-term load intensity necessitated biggest residual displacement.

After elimination of a long-term load, there were no reversible displacements between concrete and the external composite layer. Accordingly, shear stresses reduced stiffness of the concrete and carbon fibre composite joint during a long-term load action period.

4. Evaluation of experimental and theoretical research

The accomplished analysis of calculated and experimental deflection results showed that the calculated deflections of beams are 15 % higher when the composite layer isn't additionally anchored. When the external composite layer is additionally anchored with metal plates, the calculated deflections are up to 21 % higher than the experimentally determined one. If the composite layer is additionally anchored with metal or carbon fibre composite clamps, the calculated deflections are up to 8 % and 13 % higher.

The calculated deflections of strengthened beams whose reinforcement ratio $\mu_s = 0{,}388\ \%$ in various time intervals are up to 11 % higher than the experimental ones. The calculated deflections of strengthened beams whose reinforcement ratio $\mu_s = 1{,}29\ \%$ and $\mu_s = 1{,}76\ \%$ in various time intervals are up to 14 % and 18 % higher than the experimentally determined ones.

The calculated results of the load carrying capacity of strengthened beams when reinforcement ratio $\mu_s = 0{,}388\ \%$, were up to 27 % higher than the experimentally determined ones. The proposed methodology was more accurate when reinforcement ratio reached $\mu_s = 1{,}29\ \%$ and $\mu_s = 1{,}76\ \%$. Respectively, the calculated load carrying capacity varied from 1 % to 12 %.

The accomplished calculation analysis showed that the proposed calculation method based on the built-up bars theory is suitable for calculation of deflection and load carrying capacity of reinforced concrete beams strengthened with CFRP or GFRP.

General conclusions

1. A calculation methodology of deflections of reinforced concrete beams strengthened with carbon fibre composite is proposed. The calculation methodology can estimate the long-term load influence on the stiffness alteration of the concrete and carbon fibre composite joint. The influence of shear creep deformations on the concrete and carbon fibre composite joint is evaluated. Also, a new bending stiffness expression which can evaluate an additional load increment is proposed.
2. A load carrying calculation methodology of reinforced concrete beams strengthened with carbon fibre composite is proposed. The calculation methodology evaluates the stiffness alteration of the concrete and carbon fibre composite joint. The evaluation of shear creep deformations allowed decreasing the load carrying capacity of strengthened beams.
3. The behaviour of strengthened beams with a carbon fibre composite showed that shear creep deformations in the joint of concrete and carbon fibre composite increase and the joint stiffness decreases. Experimental tests identified that the load carrying capacity of a strengthened reinforced concrete beam after a long-term load action decreases up to 32 %.
4. It was experimentally determined that the deflection increment after strengthening of the beams depended on the additional anchoring method of the external composite layer and the long-term load intensity. When the long-term load intensity of the load carrying capacity of control beams was 78 %; 62 % and 43 %, the deflection during the first 100 days of the long-term load action respectively increased by 29,3 %, 26,7 % and 32,2 %.
5. Additional anchoring of the external fibre composite layer allowed increasing the stiffness of the concrete and composite layer joint and decreasing the deflection increment. The most effective anchoring method is with carbon fibre clamps. When the external composite layer was additionally anchored with carbon fibre clamps, the deflection increment during the first 100 days of the long-term load action was 2,13; 1,79 and 1,2 times lower in comparison with the beams where the composite layer wasn’t

additionally anchored or additionally anchored with metal plates, or additionally anchored with metal clamps.

6. The calculated long-term deflections of strengthened beams were 1 % – 18 % higher than the experimental ones. When the external composite layer was additionally anchored with metal plates, metal or carbon fibre clamps, the calculated deflections were 2 % – 21 % higher than the experimentally determined ones. The calculated deflections according to FIB bulletin 14 methodology were 1,4 – 2,6 times lower than it was determined experimentally.
7. The load carrying capacity of strengthened reinforced concrete beams calculated with the help of the proposed methodology was 1 % – 12 % lower than it was determined experimentally.

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Mykolas Daugevičius was born on 28 of March, 1982. He began his studies at Vilnius Gediminas Technical University in 2000. The first degree of civil engineering gained in 2004 from the Faculty of Civil Engineering. From the same faculty he gained a diploma of Master of Science of Civil Engineering in 2006. In 2006–2010 was PhD student of Vilnius Gediminas Technical University in Reinforced Concrete and Masonry Structures Department.

ILGALAIKĖS APKROVOS ĮTAKA ANGLIES PLUOŠTU SUSTIPRINTŲ LENKIAMŲJŲ GELŽBETONINIŲ ELEMENTŲ ELGSENAI

Problemos formulavimas. Anglies pluošto kompozitas vis plačiau naudojamas statybinėms konstrukcijoms stiprinti. Apie perspektyvų jo taikymą byloja eksperimentinių tyrimų gausa, efektyvus sustiprintų konstrukcijų darbas bei atsirandančios projektavimo rekomendacijos statybinėms konstrukcijoms stiprinti. Daugelyje šalių tobulinamos konstrukcijų stiprinimo anglies pluošto kompozitu technologijos. Statybinės konstrukcijos šiuo kompozitu dažniausiai stiprinamos sukuriant išorinį kompozito sluoksnį, perimantį papildomas įražas, kurioms stiprinamoji konstrukcija nesugeba priešintis. Eksperimentiniais tyrimais įrodyta, kad anglies pluošto ir betono jungtis nėra standi, todėl ilgalaikės apkrovos poveikis sumažins jungties standumą ir įtakos sijos elgseną.

Sustiprintos konstrukcijos elgsenai didelę įtaką turi apkrovos poveikio trukmė bei apkrovimo intensyvumas. Tokių tyrimų trūksta, todėl svarbu ištirti sijų elgseną esant skirtingam ilgalaikės apkrovos intensyvumui ir skirtingam išorinės anglies pluošto kompozito armatūros inkaravimui.

Darbo aktualumas. Betono ir kompozito jungtyje besivystančios šlyties deformacijos sumažina jungties standumą ir kompozitinis sluoksnis pasislenka stiprinamojo elemento atžvilgiu. Todėl sumažėja sijų laikomoji galia ir padidėja įlinkis. Aktualu ištirti sustiprintų sijų elgseną esant ilgalaikiam apkrovų poveikiui, nes betono ir kompozito jungtyje vystosi šlyties valkšnumo deformacijos, kurios papildomai sumažina laikomąją galią bei padidina įlinkius.

Tyrimo objektas. Tyrimo objektas – veikiant ilgalaike statine apkrova lenkiamųjų gelžbetoninių sijų, tempiamojoje zonoje sustiprintų anglies pluošto kompozitu, elgsenos analizė.

Darbo tikslas. Šio darbo tikslas – atlikti eksperimentinius tyrimus ir nustatyti ilgalaikės statinės apkrovos poveikį sustiprintų gelžbetoninių sijų elgsenai. Pritaikyti sudėtinių strypų teoriją ilgalaikio sijų įlinkio ir laikomosios galios skaičiavimui, įvertinant betono ir anglies pluošto jungties standumo pokytį bėgant laikui.

Darbo uždaviniai

Darbo tikslui pasiekti keliami šie uždaviniai:

1. Atlikti eksperimentinių tyrimų apžvalgą, susijusią su lenkiamųjų sustiprintų sijų elgsena ir jos sudedamųjų elementų įtaka bendram sijos darbui. Išanalizuoti skaičiavimo metodus, leidžiančius vertinti ilgalaikės apkrovos poveikį sijos įlinkiui.
2. Atlikti eksperimentinius lenkiamųjų sijų tyrimus. Nustatyti sijų elgseną esant ilgalaikei statinei apkrovai. Išmatuoti sluoksnių deformacijas ir sijų įlinkio kitimą ilgalaikio bandymo metu. Nustatyti, kaip sijų laikomoji galia priklauso nuo ilgalaikės apkrovos poveikio.
3. Eksperimentinių tyrimų rezultatus palyginti su pasiūlytos skaičiavimo metodikos, grindžiamos sudėtinių strypų totija, rezultatais.
4. Atlikti tyrimų rezultatų analizę ir pasiūlyti anglies pluošto kompozito papildomo tvirtinimo metodą.

Tyrimų metodika. Ilgalaike statine apkrova atliekami eksperimentiniai sustiprintų lenkiamųjų sijų tyrimai. Sijos stiprinamos anglies pluošto kompozitu. Sijų įlinkiai ir laikomoji galia skaičiuojama taikant metodiką, grindžiamą sudėtinių strypų teorija, įvertinant betono ir anglies pluošto kompozito jungties standumo pokytį bėgant laikui.

Darbo mokslinis naujumas

Rengiant disertaciją buvo gauti inžinerijos mokslui nauji rezultatai

1. Įvertinta anglies pluošto kompozito įtaka sustiprintos sijos standumui, atsižvelgiant į supleišėjusius gelžbetoninės sijos tempiamus ruožus veikiant ilgalaikei statinei apkrovai.
2. Eksperimentais ištirtas ir teoriškai aprašytas betono ir anglies pluošto kompozito jungties standumo kitimas bėgant laikui.
3. Eksperimentiniais tyrimais įrodyta, kad ilgalaikės apkrovos poveikis sukelia betono ir kompozito jungties šlyties valkšnumo deformacijas. Tai sumažina sustiprintos konstrukcijos standumą ir laikomąją galią.

4. Pasiūlyta gelžbetoninių lenkiamųjų elementų, tempiamojoje zonoje sustiprintų anglies pluošto kompozitu, įlinkių skaičiavimo metodika, įvertinanti betono ir anglies pluošto kompozito jungties standumo pokytį bėgant laikui.
5. Pasiūlyta gelžbetoninių lenkiamųjų elementų, sustiprintų anglies pluošto kompozitu, laikomosios galios skaičiavimo metodika vertinant ilgalaikės apkrovos poveikį.

Darbo rezultatų praktinė reikšmė. Atlikta ilgalaike apkrova veikiamų sustiprintų lenkiamųjų elementų elgsenos analizė. Nustatyta anglies pluošto kompozito ir betono jungties šlyties valkšnumo deformacijų įtaka lenkiamųjų elementų standumui ir laikomajai galiai. Tyrimais įrodyta, kad būtina įvertinti jungties standumą bei betono ir anglies pluošto jungties šlyties valkšnumo deformacijų įtaką lenkiamųjų elementų įlinkiui ir laikomajai galiai. Pasiūlyta skaičiavimo metodika, leidžianti įvertinti betono ir anglies pluošto kompozito jungties standumą, pritaikyta skaičiuoti sustiprintų sijų įlinkį ir laikomąją galią. Ištirta papildomo anglies pluošto inkaravimo įtaka lenkiamųjų elementų standumui ir laikomajai galiai. Nustatyta, kad praktiniam naudojimui anglies pluošto kompozito sluoksnį geriausia papildomai inkaruoti anglies pluošto apkabomis.

Ginamieji teiginiai

1. Pasiūlyta lenkiamųjų gelžbetoninių elementų, tempiamojoje zonoje sustiprintų anglies pluošto kompozitu, įlinkių ir laikomosios galios skaičiavimo metodika, įvertintina betono ir anglies pluošto kompozito jungties standumo pokytį veikiant ilgalaikei apkrovai.
2. Sustiprintų lenkiamų elementų anglies pluošto kompozito ir betono jungtyje, veikiant ilgalaikei apkrovai, papildomai atsiranda šlyties valkšnumo deformacijos, kurios sumažina sijos standumą ir laikomąją galią.
3. Anglies pluošto kompozito papildomas inkaravimas sumažino ilgalaikį sijų įlinkio prieaugį nuo 1,14 iki 1,97 karto.

Darbo apimtis. Disertaciją sudaro įvadas, keturi pagrindiniai skyriai, rezultatų apibendrinimas ir išvados, naudotos literatūros sąrašas, autoriaus publikacijų sąrašas disertacijos tema, 79 paveikslų, 13 lentelių, 115 literatūros šaltinių sąrašas. Iš viso 150 puslapių.

Pirmajame skyriuje atlikta literatūros analizė. Čia aptariama, kaip anglies pluošto kompozitas naudojamas statybinėms konstrukcijoms stiprinti, nagrinėjamas ilgalaikės apkrovos ir aplinkos poveikis anglies pluošto kompozitui, betonui, kompozito ir betono jungčiai bei gelžbetoninių sijų elgsenai. Pateikiami sustiprintų sijų elgsenos eksperimentinių tyrimų, veikiant trumpalaike ir ilgalaike apkrova, rezultatai. Aptariamos skaičiavimo metodikos, vertinančios ilgalaikį apkrovos poveikį.

Antrajame skyriuje pateikiama skaičiavimo metodika, grindžiama sudėtinių strypų teorija, skirta sustiprintų anglies pluošto kompozitu, sijų įlinkiui ir laikomajai galiai skaičiuoti. Metodikoje vertinamas ilgalaikės apkrovos poveikis betono ir anglies pluošto kompozito jungties standumui.

Trečiajame skyriuje pateikiami eksperimentiniai tyrimai, aprašomos bandinių charakteristikos ir jų bandymo metodikos. Nagrinėjama ilgalaikės apkrovos įtaka sijos laikomajai galiai.

Ketvirtajame skyriuje lyginami eksperimentinių tyrimų, taikant skaičiavimo metodikas, rezultatai.

Darbo pabaigoje apibendrinami rezultatai ir pateikiamos išvados.

Disertacijos tema išspausdinti septyni moksliniai straipsniai: keturi straipsniai periodiniuose recenzuojamuose leidiniuose, trys straipsniai konferencijų pranešimų medžiagose. Tyrimų rezultatai buvo skelbti 11-oje ir 12-oje Lietuvos jaunųjų mokslininkų konferencijoje *„Mokslas – Lietuvos ateitis“,* respublikinėje konferencijoje *„Statybinės konstrukcijos“* ir 10-oje tarptautinėje konferencijoje *“Modern Building Materials, Structures and Techniques”*.

Bendrosios išvados

1. Pasiūlyta lenkiamų gelžbetoninių konstrukcijų sustiprintų anglies pluošto kompozitu įlinkių skaičiavimo metodika, kuri įvertina gelžbetoninio ir kompozitinio elemento jungties standumą veikiant ilgalaikei apkrovai. Pasiūlyta metodika leidžia apskaičiuoti jungties standumą atsižvelgiant į jungties šlyties valkšnumo deformacijas. Įvertinama naujai atsirandančių statmenųjų plyšių įtaka sustiprintos sijos lenkiamajam standumui.
2. Pasiūlyta sustiprintos gelžbetoninės sijos laikomosios galios skaičiavimo metodika naujai įvertinanti sluoksnių jungties standumą. Skaičiuojant sijų laikomąją galią siūloma įvertinti šlyties valkšniųjų deformacijų įtaką.
3. Eksperimentiniais tyrimais patvirtinta, kad betono ir anglies pluošto kompozito jungtyje vystosi šlyties valkšnumo deformacijos, ir mažėja jungties standumas. Atlikus sijų laikomosios galios eksperimentinius tyrimus nustatyta, kad betono ir anglies pluošto kompozito jungties standumo mažėjimas sijų laikomąją galią sumažino iki 32 %.
4. Eksperimentiniai tyrimai rodo, kad įlinkio prieaugio intensyvumas priklauso nuo papildomo anglies pluošto kompozitinio sluoksnio inkaravimo metodo ir apkrovos veikimo intensyvumo. Sustiprintų sijų, kurių ilgalaikės apkrovos intensyvumas sudarė 78 %, 62 % ir 43 % kontrolinių sijų laikomosios galios, įlinkis pirmų šimto parų ilgalaikės apkrovos veikimo laikotarpyje padidėjo atitinkamai 29,3 %, 26,7 % ir 32,2 %.

5. Anglies pluošto kompozito papildomas inkaravimas, didina betono ir kompozito jungties standumą, tuo pačiu sumažina pradinį sijų įlinkį. Nustatyta, kad efektyviausias kompozitinio sluoksnio papildomo inkaravimo metodas yra anglies pluošto apkabos. Kai kompozitinis sluoksnis papildomai inkaruotas anglies pluošto apkabomis, sijų įlinkio prieaugis pradiniame šimto parų ilgalaikės apkrovos veikimo laikotarpyje atitinkamai buvo 2,13; 1,79 ir 1,2 karto mažesnis lyginant su sijomis, kuriose kompozitinis sluoksnis papildomai neinkaruotas arba papildomai inkaruotas plieninėmis plokštelėmis, arba papildomai inkaruotas plieninėmis apkabomis.
6. Anglies pluošto kompozitu sustiprintų sijų teoriniai ilgalaikiai įlinkiai apskaičiuoti pagal siūlomą metodiką 1 % – 18 % didesni už eksperimentinius. Kai anglies pluošto kompozitinis sluoksnis papildomai inkaruotas plieninėmis plokštelėmis, plieninėmis ar anglies pluošto apkabomis, apskaičiuotasis įlinkis 2 % – 21 % didesnis už eksperimentinį. Teoriniai sustiprintų sijų įlinkiai apskaičiuoti pagal FIB bulletin 14 projektavimo rekomendacijas yra 1,4 – 2,6 karto mažesni už eksperimentinius.
7. Siūloma skaičiavimo metodika apskaičiuota anglies pluošto kompozitu sustiprintų sijų laikomoji galia yra 1 % – 12 % mažesnė už sijų eksperimentinę laikomąją galią.

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INFLUENCE OF LONG-TERM LOAD ON THE BEHAVIOUR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CARBON FIBRE COMPOSITE

Summary of Doctoral Dissertation
Technological Sciences, Civil Engineering (02T)

Mykolas DAUGEVIČIUS

ILGALAIKĖS APKROVOS ĮTAKA ANGLIES PLUOŠTU SUSTIPRINTŲ LENKIAMŲJŲ GELŽBETONINIŲ ELEMENTŲ ELGSENAI

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