17-osios Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis“ teminė konferencija
Proceedings of the 17th Conference for Junior Researchers „Science – Future of Lithuania“

STATYBA / CIVIL ENGINEERING

2014 m. kovo 19–28 d. Vilnius
19-28 March 2014, Vilnius, Lithuania

eISSN 2029-7149
eISBN 978-609-457-694-2

INVESTIGATION OF DEFORMATION AND CRACKING BEHAVIOR OF RC TIES STRENGTHENED WITH FRP SHEETS

Darius Kesminas[1], Vytautas Tamulėnas[2]

Vilnius Gediminas Technical University

E-mail: [1]darius.kesminas@stud.vgtu.lt, [2]vytautas.tamulenas@vgtu.lt

Abstract. With increasing needs of structural rehabilitation, externally bonded sheets of fiber reinforced polymers (FRP) have become significant in the last 20 years. This paper focuses on cracking and tension-stiffening of reinforced concrete ties strengthened with basalt fiber reinforced polymer (BFRP) sheets. Test results on tension-stiffening effect regarding to the different number of BFRP layers are reported and analyzed. The analysis is based on test results of six RC ties of one meter length. It was shown that the BFRP sheets are able to constrain the crack opening. Subsequently, the mechanical properties of selected adhesive have to be considered and could not be neglected in the design.

Keywords: Cracking, Fiber Reinforced Polymer, Strengthening, Reinforced Concrete, Tension-Stiffening.

Introduction

Strengthening of concrete structures with FRP materials has become relevant in the last decades since the demands of structures substantially changes in time. Bridges deck slabs, columns and girders have to carry higher loads and comply with forthcoming design standards. Furthermore, ageing and deterioration of civil engineering structures lead to increased maintenance costs and subsequently require a replacement. However, it is not always economically possible to change an existing structure with a new one. Therefore, the challenge must be taken to develop rather simple method such as strengthening that can be used to extend the serviceability life of structures.

Along with the traditional strengthening methods, e.g. modification of static structural system, change of cross section or external pre-stressing, a promising alternative is the use of fiber reinforced polymer sheets. The exceptional properties of FRPs, like high tensile strength, corrosion resistance and durability, make the life-cycle cost lower than conventional materials. Additionally, a strengthening with FRP poses a number of advantages such as press-stressing possibilities, reduced time of construction, easy handling and transportation of materials (Täljsten 2006).

However, many problems and uncertainties still remain regarding the application and design of FRP reinforced concrete elements. There is still a lack of design procedures for the application of the external FRP reinforcements. Furthermore, an attention should be paid to the long-term degradation of mechanical properties, proper selection of FRP material in a severe environmental conditions, and, especially, to the bond properties as the governing criteria for deformational analysis (Gudonis *et al.* 2013). The understanding of development of the bond stresses within the interface could be very important for the structural behavior of RC elements. For example, the failure of RC ties externally bonded with FRP sheets could be governed by a premature failure of the interface between FRP sheets and concrete (Biscaia *et al.* 2013).

The intact concrete between cracks carries tensile force due to the bond between the steel and concrete. The average tensile stress in the concrete can be a significant fraction of the tensile strength of concrete. This effect is called by tension-stiffening and is often accounted for in design by an empirical adjustment to the stiffness of the fully cracked cross-section. Ceroni *et al.* (2004) and Pecce *et al.* (2004) have experimentally investigated tension-stiffening effect in FRP strengthened RC ties.

In this paper the results of experimental tests on RC ties strengthened with BFRP sheets are provided. Comparing elements without and with different number of layers of BFRP sheets, cracking and the tension stiffening are analyzed. The need of additional anchorage for FRP sheets has been examined paying attention to the delamination of external reinforcement.

eISSN 2029-7149
eISBN 978-609-457-694-2

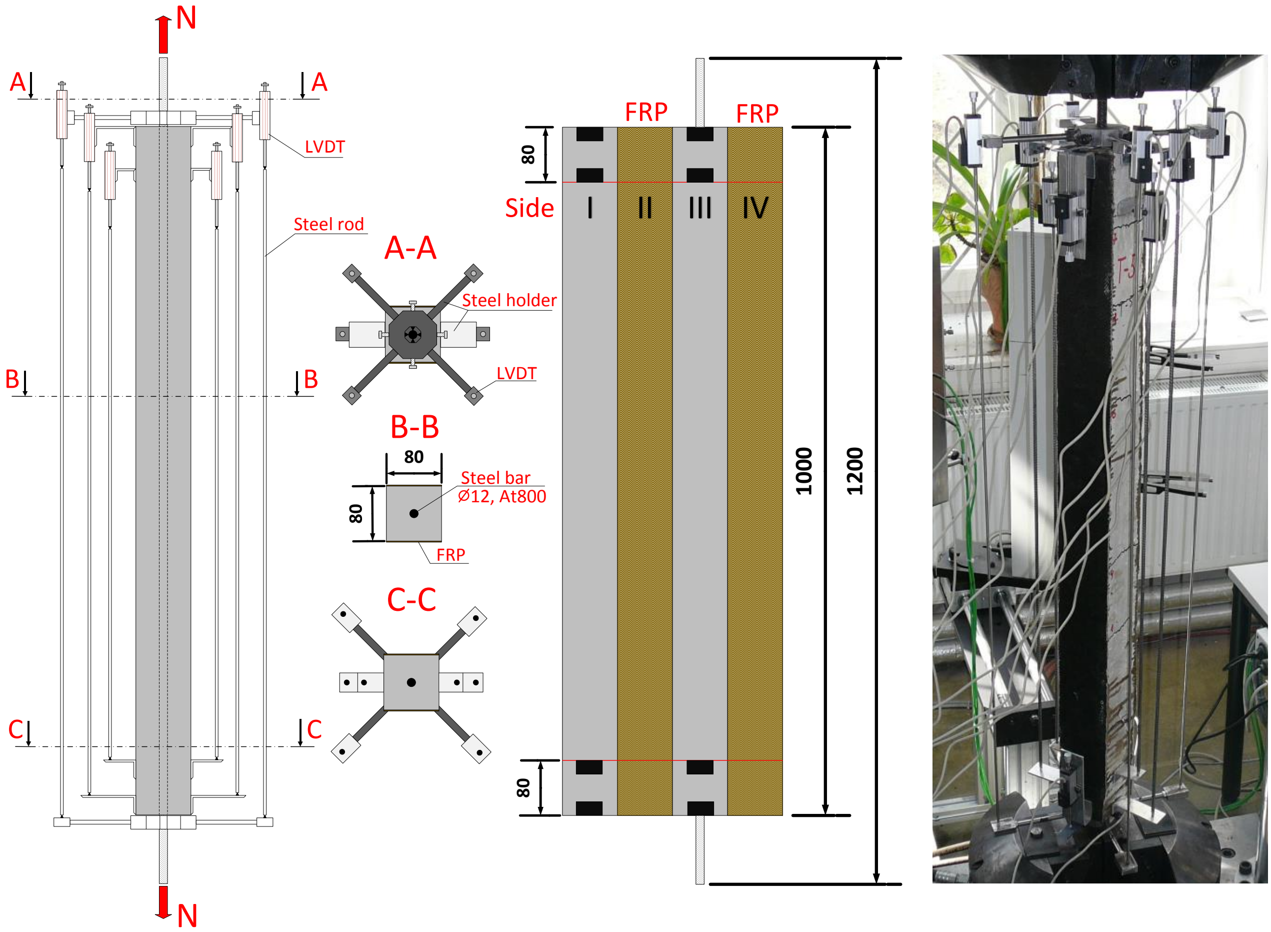

Fig. 1. Test setup

Test Setup and Material Properties

Six RC ties were tested by applying a tensile force according to the test setup shown in Fig. 1. The concrete specimen is a 1000 mm long prism with a square cross section of 80 mm x 80 mm. The series consists of two reference specimens and four others externally strengthened with FRP sheets. The internal steel reinforcement contains one continuous central steel bar (diameter Ø12 mm).There are two specimens strengthened with 1 layer of BFRP (basalt fiber reinforced polymer), one with 2 layers of BFPR, and one with 3 layers of BFRP. The layers of basalt fibers were applied on two opposite sides along the entire length of every specimen These FRP sheets are made of bi-directional basalt fibers (one layer mass per area equal to 400 g/m^2). Tensile tests were performed on the basalt fiber composites of specimens with a different number of layers (refer to Table 1). The equipment used for the tensile test of basalt fibers is shown in Fig. 2. Steel plates were attached at the ends to give a better grip. The tensile strength, ultimate strain, and axial stiffness obtained by the tensile test are presented in Table 1.

In order to provide the necessary bond to the specimen surface, the sheets have to be impregnated by epoxy resin. The wet lay-up system was used for BFRP reinforcement. The BFRP sheets were glued to the surface

Table 1. Reinforcement Properties

Type		Dimension, mm	Yield stress f_y, MPa	Tensile strength, MPa	Ultimate strain, %	Axial stiffness, MN
Rebar At800		Ø = 12	945	f_{su} = 1120	ε_{su} = 12.5	$A_s E_s$ = 21.49
Basalt	1 layer	b = 65.78 t_f = 0.860	—	f_{fu} = 116.6	ε_{fu} = 2.34	$A_{frp} E_{frp}$ = 0.277
	2 layer	b = 68.49 t_f = 1.470	—	f_{fu} = 167.5	ε_{fu} = 2.78	$A_{frp} E_{frp}$ = 1.017
	3 layer	b = 68.49 t_f = 2.036	—	f_{fu} = 169.6	ε_{fu} = 2.44	$A_{frp} E_{frp}$ = 1.558

Fig. 2. Tensile test process on BFRP sheet specimens

using three component epoxy resin (Polyforce plus). Sheets were hand-pressed to the concrete surface with a brush roller to have better adhesion. The epoxy resin was allowed to cure for 5 days before testing.

High-strength At800 bars were used as internal steel reinforcement. Tensile tests were performed on three specimens with diameter Ø12 mm. The mean values of yielding stress, tensile strength, ultimate strain, and deformation modulus are given in Table 1.

Normal strength concrete (NSC) was used for all the specimens; the concrete composition is given in Table 2. The concrete age was over 28 days on the testing day. The mean values of cylinder, cubic and tensile strength of concrete f_{cm}, $f_{c,cub}$, f_{ctm}, respectively, as well as the deformation modulus in compression E_c, and the density of concrete are reported in Table 3.

The main characteristics of all the specimens are presented in Table 4, where the following notations are used: $\rho_s = A_s / A_c$, the ratio of internal reinforcement, where A_s – steel area and A_c – concrete area; $\rho_{frp} = A_{frp} / A_c$, the ratio of external reinforcement where A_{frp} – FRP area; $\rho_{eq} = \rho_s + \rho_{frp} \cdot E_{frp} / E_s$, the equivalent reinforcement ratio.

The tests were carried out in two load cycles. The first one, a preload cycle, after which strengthening with FRP was performed. Then a second load cycle, where the loading up to 70% of the ultimate stress limit of internal reinforcement was executed. During the preload cycle, concrete strains were recorded by eight linear variable displacement transducers (LVDT) on all sides of the specimen as shown in Fig. 1. Four LVDT devices were used to measure concrete strain along the entire length of every specimen as well as another four were attached 80 mm from the ends of specimens. For the second load cycle in order to apply an externally bonded FRP reinforcement on sides 2 and 4 (Fig. 1), the LVDT's were removed without further strain measurement on these sides. During the both load cycles, a crack development was observed and the final crack pattern indicated (see Fig. 3). All the specimens were tested with a preload cycle, as shown in Table 4. The preload values were established in order to simulate serviceability conditions of the unstrengthened specimen. Specimens were tested using a tensile testing equipment with a capacity of 600 kN in a displacement-controlled way. Tensile force was applied by gripping the steel bars. The loading rate was 0.1 mm/min for the both load cycles.

Table 2. Mixture of Normal Strength Concrete

Material	Normal strength concrete
Granite gravel 4/8	404 kg
Granite gravel 8/11	606 kg
Sand	865 kg
Portland cement: CEM II\A-LL 42,5 N	331 kg
Water	150 kg
Plasticizer: (Power Flow 3100, 1.2%)	3.97 kg

eISSN 2029-7149 / eISBN 978-609-457-694-2
http://jmk.statyba.vgtu.lt

Table 3. Mechanical and physical properties of concrete

Concrete type	Age (days)	f_{cm}, MPa	$f_{c,cub}$, MPa	f_{ctm}, MPa	E_c, GPa	Density (kg/m^3)
Normal strength	28	45.31	52.91	3.35	33.1	2398

Table 4. Main characteristics of the specimens

Specimen	Preload N_p (kN)	FRP type	FRP layers	Bar diameter (mm)	f_{cm}, MPa	ρ_s, %	ρ_{frp}, %	ρ_{eq}, %
T1-ref	—	—	—	12	45.31	1.767	—	1.767
T2-ref	—	—	—	12	45.31	1.767	—	1.767
T3-3LS	30	BFRP	3	12	45.31	1.767	2.219	1.895
T4-2LS	30	BFRP	2	12	45.31	1.767	1.573	1.845
T5-1LS	30	BFRP	1	12	45.31	1.767	0.884	1.818
T6-1LS	30	BFRP	1	12	45.31	1.767	0.884	1.790

Discussion of Experimental Results

It is known that a failure type of the strengthened RC ties is highly dependent on the stiffness of applied FRP sheets. The higher stiffness of FRP results in debonding failure at the anchorage area (Jakštaitė and Arnautov 2014). However, the increased elasticity of external reinforcement results in no slip of FRP in the anchorage zone. Current specimens were designed to investigate a need of additional anchorage for FRP fabrics, i.e. no mechanical anchorage was applied. The statement by Jakštaitė and Arnautov (2014) was proven by sufficient strength of interface between FRP and concrete without additional strengthening of anchorage zone.

Performed experimental investigation has shown that external reinforcement with BFRP sheets is effective method for strengthening RC elements as the significant constraint of the crack opening width will take place. This could be clearly seen from the increased number of cracks while applying the BFRP sheets (additional five to eight cracks appear on the strengthened RC ties (Fig. 3)). Moreover, the additional crack opening (increased number of cracks) requires fracture energy release and, therefore, increasing the tension-stiffening effect.

The load-strain diagrams of RC ties without and with FRP sheets are presented in Fig. 4 and Fig. 5, respectively. In order to compare the tension-stiffening of both strengthened and unstrengthened elements, it is necessary to eliminate shrinkage effect. For unstrengthened ties, assessment of the deformation modulus is quite trivial and could be performed following the methodology by Kaklauskas et al. (2009). However, the shrinkage elimination for externally strengthened ties is rather complicated as it was partially released after the crack opening at the preloading stage. Kaklauskas et al. (2009) showed that the shrinkage effect is proportional to average secant deformation modulus of concrete. In this study the shrinkage effect for the strengthened members was estimated in a simplified way: relating it to the average deformation modulus assessed using test data of RC ties without sheets under the same loading level.

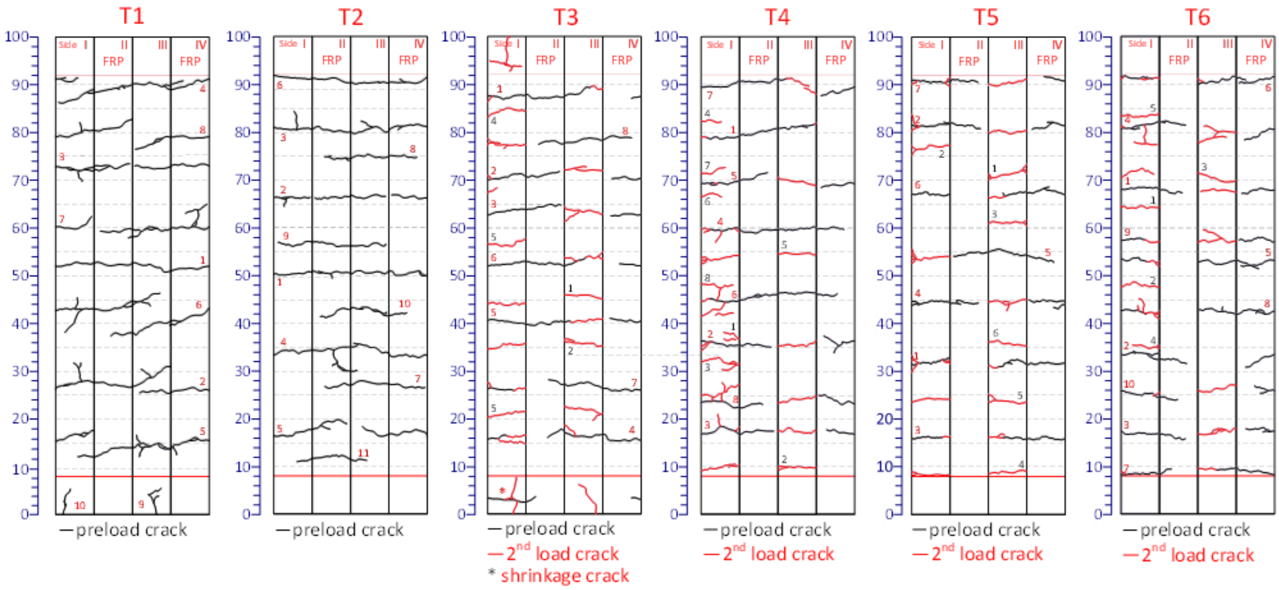

Fig. 3. Crack pattern of all the specimens

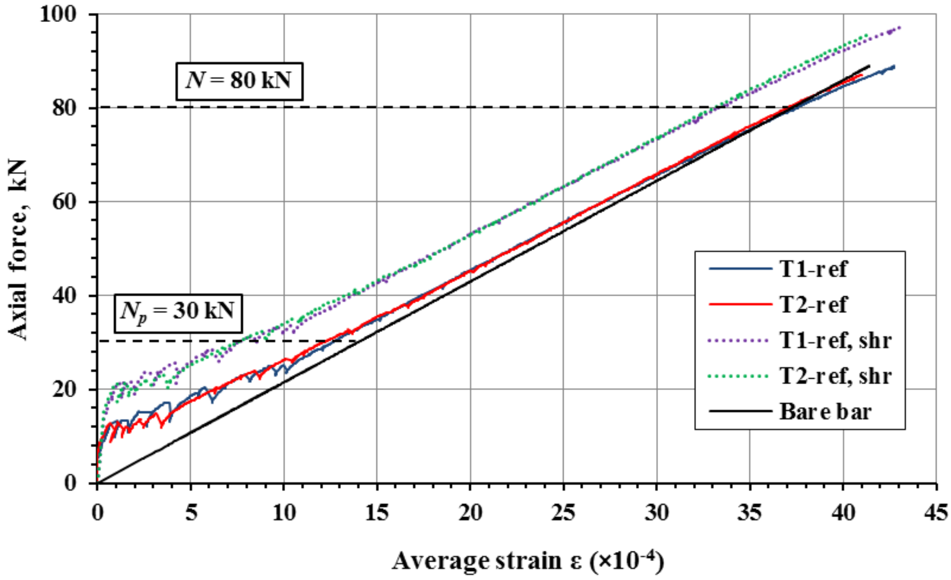

Fig. 4. Experimental and free-of-shrinkage load-strain relationships of unstrengthened RC ties

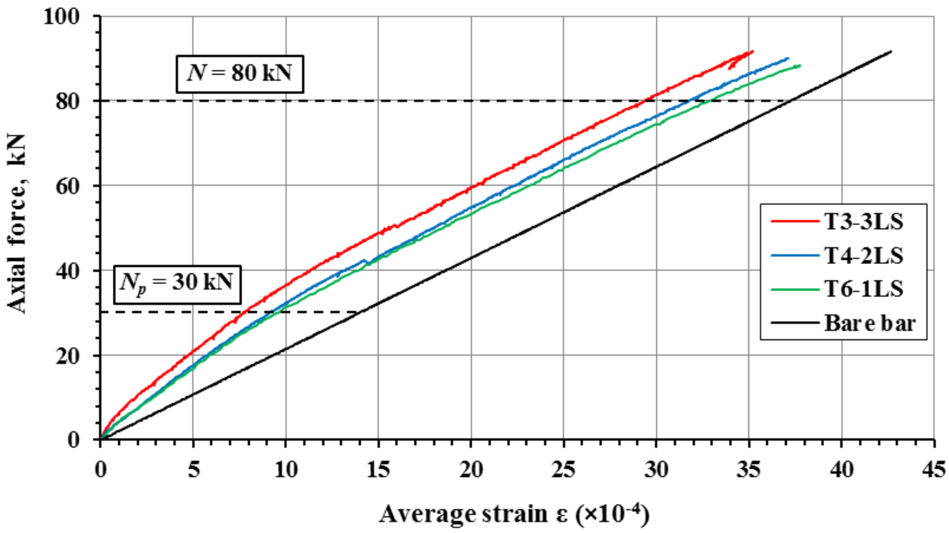

Fig. 5. Experimental load-strain relationship of strengthened RC ties

A rough schematic representation of tension-stiffening effect regarding to the number of BFRP layers is given in Fig. 6. The points corresponding to the selected load levels (i.e. 30 and 80 kN) are considered. The same phenomenon of the tension-stiffening increment has been observed. Tension-stiffening effect increases with increasing deformations and depends on the amount of BFRP material. As could be seen from the Fig. 6, at least one layer of BFRP sheets has a significant influence on the behavior of tension-stiffening. In order to determine an adequate number of FRP sheets, the qualitative analysis and additional experimental research have to be performed.

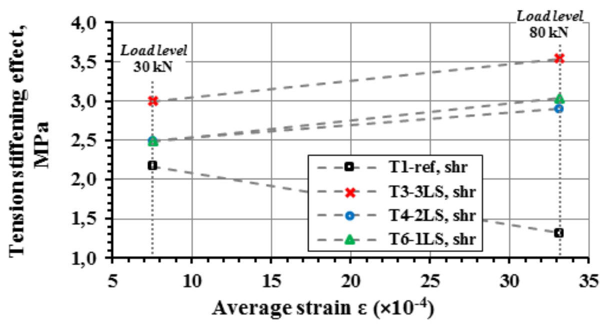

Fig. 6. Simplified representation of tension-stiffening effect

Furthermore, recent investigation conducted by the authors has revealed that the mechanical properties of adhesives also govern the failure mode. In case of the elastic epoxy resin is used for gluing the FRP sheets to the surface of concrete, no delamination has been observed. On the other hand, if the stiffer epoxy resin is applied, the debonding of FRP sheets may occur. It should be pointed out that the elasticity of adhesives is also important and could not be neglected in the design.

Conclusions

This paper investigates deformation and cracking behavior of RC ties strengthened with basalt fiber reinforced polymer (BFRP) sheets. The analysis is based on test results of six RC ties of one meter in length. From the performed analysis, the following two main conclusions can be drawn:

1. The BFRP sheets are able to constrain the crack opening. The number of cracks in unstrengthened elements was 8 to 10, whereas the strengthening increases this number up to 16.

2. The delamination of experimental specimens did not occurred. It can be related to high elasticity of the external strengthening. The increased stiffness of FRP most probably results in debonding failure at the anchorage area. The elasticity of adhesives is also important and could not be neglected in the design.

Acknowledgments

Vytautas Tamulėnas gratefully acknowledges the financial support provided by the *Research Council of Lithuania* (Research Project MIP–050/2014). The authors gratefully acknowledges for the experimental materials provided by the UAB “Poliforsa”.

References

Biscaia, H. C.; Chastre, C.; Silva, M. A. 2013. Linear and nonlinear analysis of bond-slip models for interfaces between FRP composites and concrete. *Composites Part B: Engineering* 45(1), 1554–1568.

Ceroni, F.; Pecce, M.; Matthys, S. 2004. Tension Stiffening of Reinforced Concrete Ties Strengthened with Externally Bonded Fiber-Reinforced Polymer Sheets, *Journal of Composites for Construction* 8(1): 22–32.

Gudonis, E.; Timinskas, E.; Gribniak, V.; Kaklauskas, G.; Arnautov, A. K.; Tamulėnas, V. 2013. FRP reinforcement for concrete structures: state-of-the-art review of application and design. *Engineering Structures and Technologies* 5(4), 147–158.

Jakštaitė, R; Arnautov, A. K. 2014. Išoriškai FRP lakštais sustiprintų gelžbetoninių elementų skaitinis modeliavimas. *Mokslas – Lietuvos ateitis, Statyba*. Submitted for publication.

Kaklauskas, G.; Gribniak, V.; Bacinskas, D.; Vainiunas, P. 2009. Shrinkage influence on tension stiffening in concrete members. *Engineering Structures* 31(6), 1305–1312.

Pecce, M.; Ceroni, F. 2004. Modeling of Tension-Stiffening Behavior of Reinforced Concrete Ties Strengthened with Fiber Reinforced Plastic Sheets, *Journal of Composites for Construction* 8(6): 510–518.

Täljsten, B., 2006. *FRP Strengthening of Existing Concrete Structures. Design Guideline*. Division of Structural Engineering, Luleå University of Technology, 4th Ed, Luleå, 227 p.

POLIMERO LAKŠTAIS SUSTIPRINTŲ TEMPIAMŲJŲ GELŽBETONINIŲ ELEMENTŲ DEFORMACIJŲ IR PLEIŠĖJIMO TYRIMAI

D. Kesminas, V. Tamulėnas

Santrauka

Pastaraisiais metais, didėjant statybinių konstrukcijų atnaujinimo poreikiui, išoriškai tvirtinami pluoštu armuoti polimeriniai lakštai (angl. *fiber reinforced polymers – FRP*) tapo ypatingai reikšmingi konstrukcijų stiprinimui. Šiame straipsnyje aptariami tempiamųjų gelžbetoninių elementų, išoriškai sustiprintų bazalto pluoštu armuotais lakštais, pleišėjimas ir tempiamojo sustandėjimo efektas. Tyrimo metu analizuojamas tempiamų bandinių, sustiprintų skirtingu bazalto pluošto lakštų skaičiumi, tempiamojo sustandėjimo efektas. Atlikta eksperimentinė programa, kurią sudaro šeši 1 m ilgio gelžbetoniniai bandiniai. Gelžbetoninių elementų tempimo bandymų rezultatai leidžia teigti, kad, adekvačiam bazalto pluoštu sustiprinto elemento suirimo pobūdžiui nustatyti, būtina įvertinti klijų, kuriais tarpusavyje suklijuoti lakštai, mechanines savybes. Taip pat tyrimo metu nustatyta, kad BFRP lakštai efektyviai varžo gelžbetoninių elementų plyšių atsivėrimą ir sumažina jų plotį.

Reikšminiai žodžiai: pleišėjimas, pluoštu armuoti polimerai, stiprinimas, gelžbetonis, tempiamasis sustandėjimas.