Experimental verification of the shear load-carrying capacity of adhesively bonded joints

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Abstract: - This paper is focused on the description of particular results in case of loading tests of the adhesively bonded joints of glass-fibre reinforced plastic composite members subjected to a shear force. It describes the determination of their characteristic and design values of load-carrying capacity according to “Design assisted by testing” method given by Eurocode, as well as their actual behaviour through the modes of failure. The results have been obtained and evaluated on the basis of group of loading tests divided into five series of specimens with a slightly different geometric configuration as a part of the solution of the research project focused on the use of FRP composite members and their advantages in construction of civil engineering. All the performed experiments have been subsequently taken as a pilot tests for the verification of numeric models of the designed connection details.

Key-Words: - composite members, adhesively bonded joints, loading tests, shear resistance, failure modes, load-carrying capacity determination, design assisted by testing

1 Introduction

In these days, there is very often a tendency of a use of various types of composite members in the field of civil engineering. As an example the application of these members in case of bridge structures details can be considered (e.g. parts of a bridge deck, etc.), whereas it can be advantageously used their high load-carrying capacity together with a relatively small self-weight. Then, the design of connection between composite members made of the glass-fibre reinforced plastic members (or between them and other materials) can be a very important problem.

In this context, several research projects focused on problems of a use of different types of composite members have been realized in the recent period on the author’s workplace, which is the Institute of Metal and Timber Structures at Faculty of Civil Engineering at Brno University of Technology. During their solution, some particular experiences and knowledges about the actual behaviour (failure mechanisms and failure modes) have been obtained also in case of design of the composite member connections.

One of the latest of the mentioned projects is still in solution (in co-operation with Technology agency of the Czech Republic and with the Vladimír Fišer Company). There is a main goal in this project, which is to find a sort of construction as well as an arrangement of a (foot)bridge structure in order to efficiently use the advantages of existing actual FRP profiles or their combination with other common building materials, especially steel, in case of new construction (or reconstruction).

However, there are also some other goals in this project, where one of them is to find a solution for the connection between bridge crash barriers, bridge fittings, railings, etc., and the FRP profiles without any degradation of the material advantages together with a satisfying of all safety requirements in case of bridges and (foot)bridges.

Hence, five series of the GFRP specimens with slightly different geometric parameters have been designed and selected for testing, Fig. 1. These pilot tests have been intended for the verification of the load-carrying capacities of the specimens as well as for the determination of their characteristic and design values according Design assisted by testing method given by Eurocode [1]. Next, they can be used for the verification of numerical models, too.

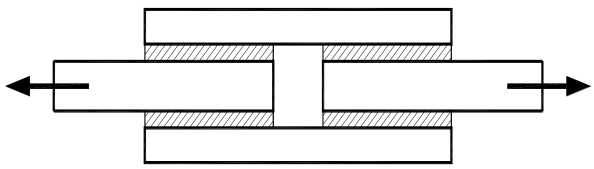

Fig. 1 Scheme of tested adhesively bonded joints

2 Arrangement of loading tests

In order to get the information about the actual behaviour as well as to obtain the values of the characteristic or design load-carrying capacities, the loading tests with using of a tension force in all selected joint specimens (with their own different geometric configurations) have been performed. This tension force, in fact, caused the shear loading and the shear stress in planes of the connection.

During all the loading tests the values of the tension (respectively shear) loading forces were recorded. The displacements were also measured and finally, for the selected specimens, the values of a shear stress through the use of the strain gauges were recorded, too. The prepared specimens are shown in Fig. 2.

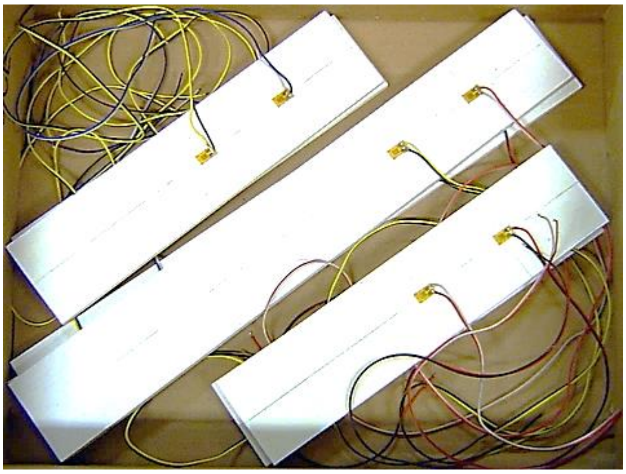

Fig. 2 Prepared specimens with the strain gauges

2.1 Description of the loading test equipment

For the realization of performed loading tests, it means for the initialization of loading forces, the electromechanical high-capacity four-column testing machine LabTest 6.1000 (with a capacity up to 1000 kN) have been used, see Fig. 3.

Fig. 3 Testing machine used for loading tests of the adhesively bonded joints

The sizes of the forces have been controlled by the appropriate software (Catman Easy by HBM) and then, the obtained data of the loading forces along with the longitudinal and transversal displacements have been recorded by the measuring centre (MGC plus by HBM). The illustration of the entire loading test arrangement is shown in Fig. 4, where the testing equipment consisted of following parts (see the numbers used in Fig. 4):

1 - Testing machine LabTest 6.1000 (LaborTech).
2 - Inductive displacement transducer WA-T 10 mm and WA-T 50 mm (HBM).
3 - Displacement transducer transducers with the strain gauges LY11-3/350.
4 - Resistance strain gauges LY41-3/120 and LY41-1,5/120.

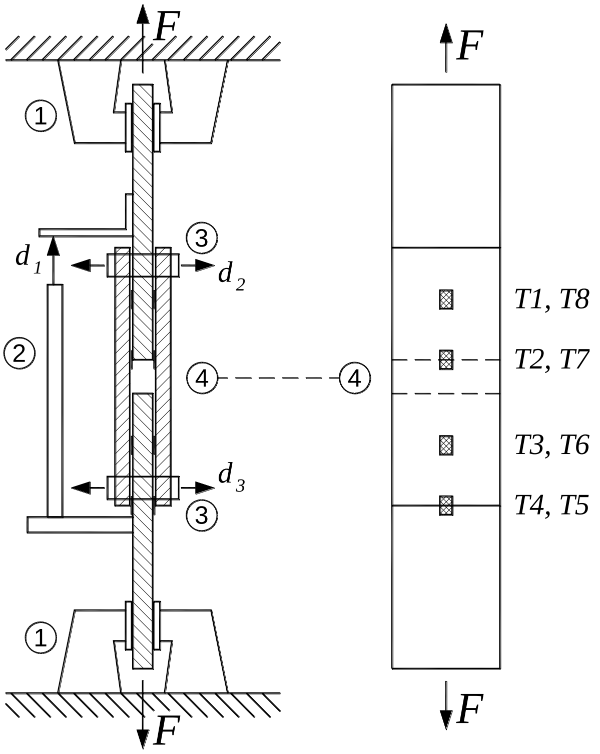

Fig. 4 Scheme of the loading test arrangement

2.2 Specification of test specimen dimensions and characteristics

The test specimens of the GFRP composite member connection have been designed as the double-lap composite-to-composite adhesive joints, which consisted (at the both ends) of two cover adherents with the thickness t_1 and of one middle adherent with the thickness t_2 (Fig. 4 and Fig. 5), [2] – [5].

Then, a thickness of the adhesive t_a was 2 mm for each specimen. The width of the adherents was selected as the value w and the distance of the overlapping of the adherents was l_o (the same values at the both ends of the joint).

Two specimens with the strain gauges in each series were used, whereas eight strain gauges marked from T1 to T8 were used for each specimen in this case and placed on a specimen into the centre of shear area of the adherents and at the adherent's edge, see Fig. 4 and Fig. 2).

In one of the series skewed ends of the cover adherents have been used to get the information of their eventual influence on the value of the load-carrying capacity. By the same reason the adhesive was rounded in the area of the contact between adherents in the event of one of the series, too. Both of these described modifications can be found in the pictures on Fig. 5 and Fig. 6. Table 1 shows all the selected dimensions and parameters of the bonded joints in the event of 5 used series of specimens.

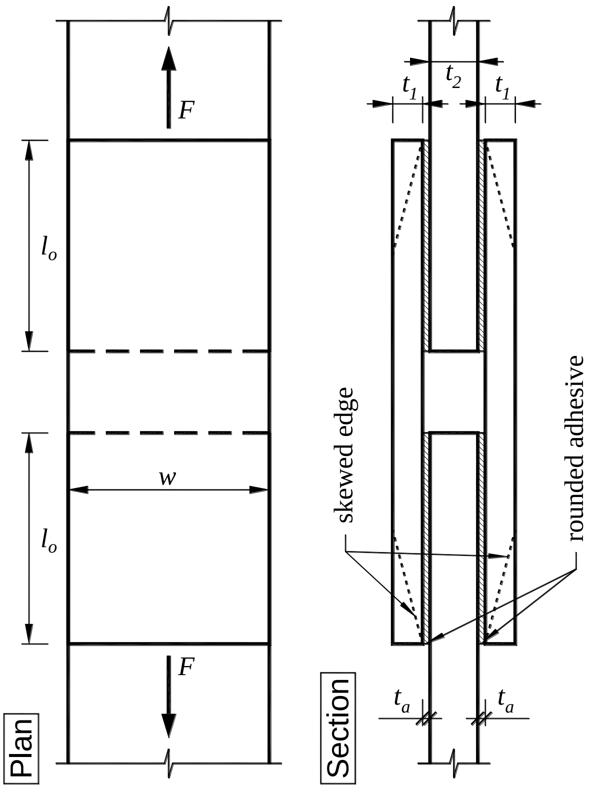

Fig. 5 Geometry and parameters of the tested adhesively bonded connection specimens

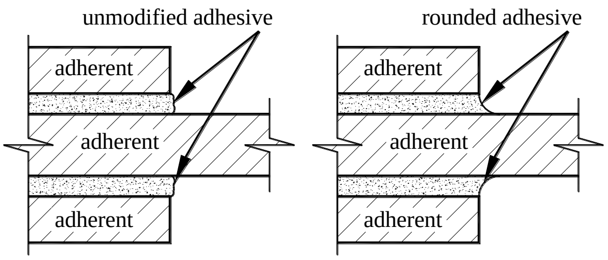

Fig. 6 Illustration of the adhesive modification

Table 1 Parameters of the adhesively bonded joint specimens (the dimensions according to Fig. 5)

Series of specimen	w	l_o	t_1	t_2	Skewed edge	Rounded adhesive
	[mm]					
1	50	50	6	9	no	no
2	50	50	6	9	no	yes
3	25	50	6	9	no	no
4	25	50	6	9	yes	
5	50	100	6	7	no	

2.3 Loading tests realization

Altogether 99 loading tests were performed on the specimens in five series marked as S1 to S5 (by 21 tests in the series S1 to S4 and then 15 tests in case of the series S5).

During all loading tests it was used the tension force F until the test specimen failed. To get the values of a tangential stress the member dimensions have been chosen in such a way so that all the specimens have failed in the shear area of the bonded joint and not in the composite member cross-section. For the illustration, some pictures of performed loading tests are shown in Fig. 7.

Fig. 7 Illustration of the loading tests realization

3 Test results

The elaboration of the test results values has been subsequently performed on the basis of 99 realized loading tests of the adhesively bonded composite joints.

First, from the "force F – time t" relationships the intervals of relevant measured data have been obtained. Then, for the chosen recorded values the relationships of "force F – displacement w" as well as "force F – relative displacement ε" have been evaluated and elaborated to the graphic form.

As an example of this elaboration, two graphs of the dependences of relative displacements ε and the loading shear forces F are shown in Fig. 8 for the series S1 and S4.

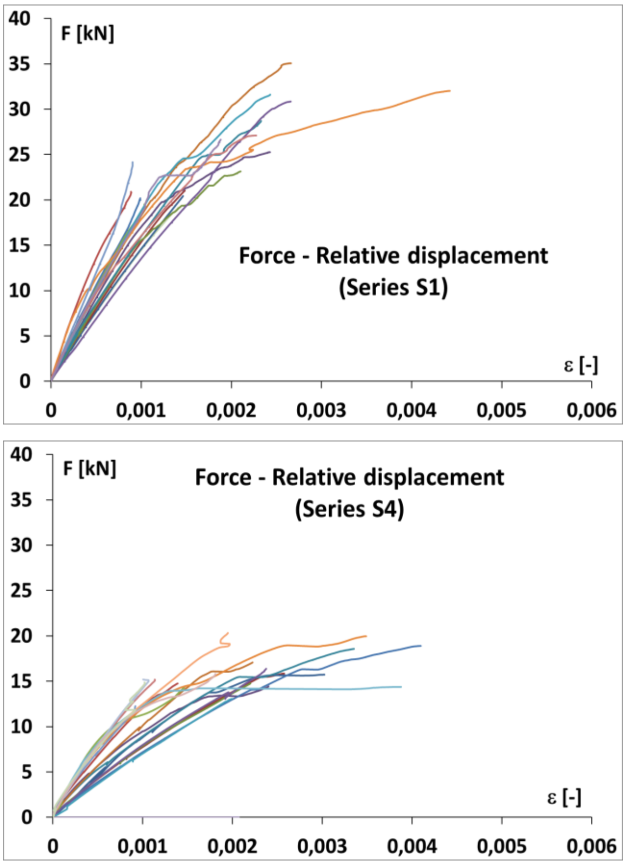

Fig. 8 Force to relative displacements relationships in case of series of specimens S1 and S4

3.1 Modes of failure

Except the obtained values of loading tests (like the loading forces, displacements, etc.), also the modes of failure have been recorded and classified. Generally, seven classes of failure modes exist in case of adhesively-bonded joints of fibre-reinforced plastic composite members. All the particular failure modes depend on a position of the separation (they can occur in the adhesive-adherent interface or within the adhesive) as well as on the appearance of the fiber reinforced plastic matrix. They are all given by the standard ASTM [6] and can be defined as follows (see next section).

3.1.1 Definition of modes of failure

The first one, so-called "Adhesive Failure", is a rupture of the adhesively bonded joint, such that the separation appears to be at the adhesive-adherent interface.

The second class, called "Cohesive Failure", is a rupture, such that the separation is only within the adhesive.

Then, the third class is the "Thin-Layer Cohesive Failure" (TLCF), which is similar to the previous one, except that the failure is very close to the adhesive-adherent interface.

The 4th class is called "Fiber-Tear Failure" (FTF) and it is mostly characterized by the appearance of the FRP matrix (i.e. reinforcing fibres) on both ruptured surfaces.

Next, 5th class, so-called "Light-Fiber-Tear Failure" (LFTF) is a failure occurring within the (G)FRP substrate, near the surface, where it is just thin layer of the resin matrix visible on the adhesive, with few or no fibers transferred from the substrate to the adhesive.

The 6th class, "Stock-Break Failure", is in-fact a break of the (G)FRP member itself, but always outside the adhesively-bonded joint region.

Finally, the last one is so called "Mixed Failure", which can be any combination of two or more of the six classes of failure mode defined above.

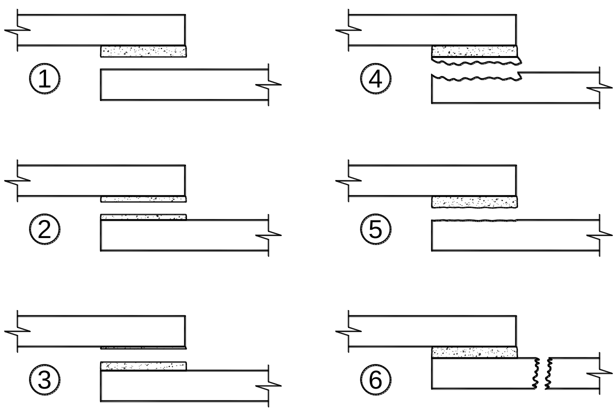

Fig. 9 Modes of failure in case of adhesively bonded joints of (G)FRP members

For the illustration of all the described modes see Fig. 9. Next, also some failed specimens are shown in Fig. 10, where an example of a specimen with the skewed edge (as described above) is shown on the bottom, (see also Fig. 5).

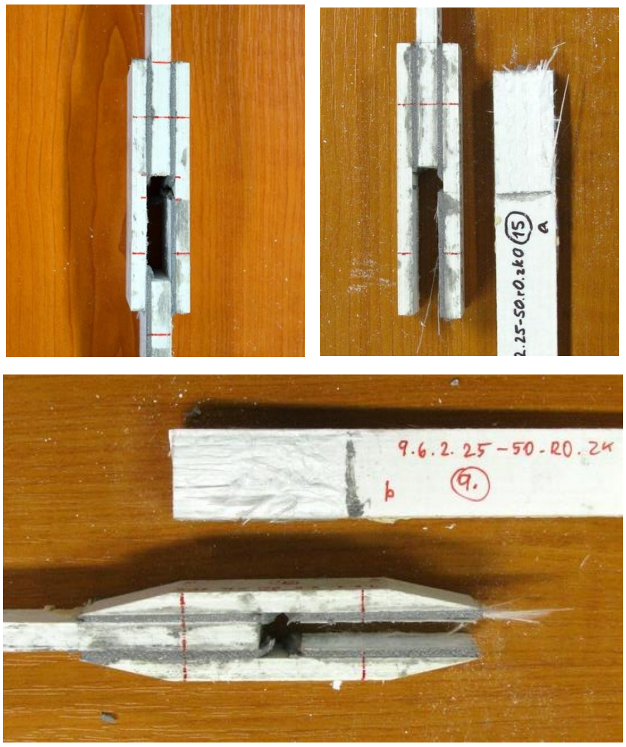

Fig. 10 Examples of failed specimens

3.1.2 Test results in case of modes of failure

Next, Table 2 shows the results from the viewpoint of described failure modes. In most cases the Fiber-Tear Failure (FTF) occurred and also the Mixed Failure, which was always a mixture of the Fiber-Tear Failure, the Light-Fiber-Tear Failure or the Adhesive Failure (or of all these three, eventually).

Table 2 Test results in case of the modes of failure of adhesively bonded joints of GFRP members

Failure modes	Series of specimen					Σ [%]
	S1	S2	S3	S4	S5	
Adhesive	1	1	-	-	-	2
Cohesive	-	-	-	-	-	0
TLCF	-	3	-	-	-	3
FTF	1	-	10	18	9	38
LFTF	2	6	-	-	-	8
Stock-break	-	-	-	-	-	0
Mixed	17	10	11	3	6	47
None	-	1	-	-	-	1
Σ	21	21	21	21	15	99

Actually, no failure occurred within the adhesive and no failure of the FRP member itself outside the connection. These results confirmed the design purpose where the adhesive wouldn't be so-called "weak" part of the connection.

As the total number of test specimens was 99, the last row of the Table 2 shows not only sum in each case, but as well (very closely) the percentage for each case of failure mode.

3.2 Load-carrying capacity verification

The achieved minimal ($F_{min,test}$) as well as maximal ($F_{max,test}$) values of the shear loading forces at the moment of the failure in case of each test series are shown in Table 3 together with the mean values ($F_{mean,test}$) and their variation coefficients (v).

Then, after previous experiences [7] – [10] the method "Design assisted by testing" given in EC [1] was used for the determination of the characteristic ($F_{ult,test,k}$) and design ($F_{ult,test,d}$) values of the ultimate load-carrying capacity in case of the shear force in the tested adhesively bonded connections; see Table 4, where the corresponding values of factors γ_f are written, too.

Table 3 Shear forces F obtained during loading tests for each series of specimen

Series	S1	S2	S3	S4	S5
$F_{min,test}$ [kN]	26,65	28,10	11,83	13,07	34,35
$F_{max,test}$ [kN]	35,06	37,28	19,32	20,33	52,44
$F_{mean,test}$ [kN]	29,77	32,48	14,7	16,21	40,31
v [-]	0,084	0,089	0,125	0,126	0,139

Table 4 Determination of a load-carrying capacity in case of a shear force F in the connection

Series	S1	S2	S3	S4	S5
$F_{ult,test,k}$ [kN]	24,15	26,35	11,48	12,64	30,00
$F_{ult,test,d}$ [kN]	16,86	18,40	8,06	8,85	17,48
γ_f [-]	1,432	1,432	1,425	1,428	1,717

The same procedure of data evaluation was used in case of the determination of characteristic and design shear resistances of the bonded joint, see Table 3. The shear stress has been obtained for the shear area, which has been taken as:

$$A_v = l_o \cdot w \qquad (1)$$

and the value of the shear stress can be written:

$$\tau_{ult} = F_{test} / (2 \cdot A_v). \qquad (2)$$

The resultant values subsequently evaluated from the loading tests are shown in Table 5 in comparison with the expected ultimate resistance $\tau_{ult,num}$ obtained from the numerical FEM models of the connection. The actual shear resistances are about 5-10 % higher in case of a skewed edge or rounded adhesive.

Table 5 Shear resistances of the composite joint

Series	S1	S2	S3	S4	S5
$\tau_{ult,num}$ [MPa]	4,72	6,45	4,72	5,87	2,65
$\tau_{mean,test}$ [MPa]	5,98	6,57	5,96	6,57	4,06
$\tau_{ult,test,k}$ [MPa]	4,85	5,33	4,77	5,13	3,00
$\tau_{ult,test,d}$ [MPa]	3,39	3,72	3,52	3,59	1,70
γ_f [-]	1,43	1,43	1,36	1,43	1,76

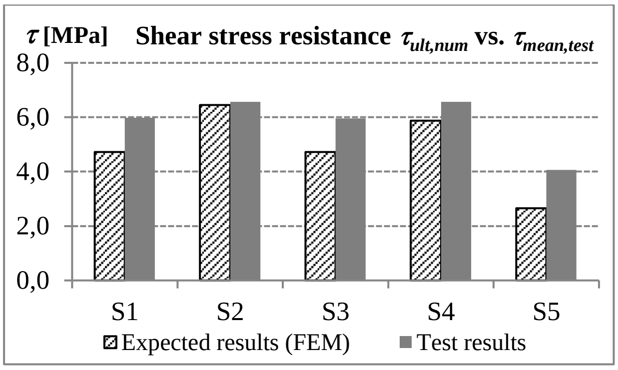

Fig. 11 Comparison of shear resistances (expected values and obtained values from the loading tests)

The graph in Fig. 11 shows the determined mean values of the shear resistances from Tab. 5 in comparison with the expected values, which have been obtained from FEM models of designed joints.

4 Conclusion

In the event of the design and development of adhesively bonded joints of GFRP composite members altogether 99 loading tests have been performed Some their results have been mentioned above as partial conclusions. All the values of the actual load-carrying capacities in case of shear loading are used for the verification of the numerical models, too.

Except that, the experiences and knowledges about the actual behaviour (especially about the process of loading, failure modes, technology of the adhesive bonding, etc.) which have been obtained during described experiments, are now subsequently used for the design and verification of another series of GFRP specimens in case of the continuing research project, in which connections of full-scale composite bridge girders and their connections with the bridge fittings, (railings, etc.), as well as with a combination of composite members and steel parts are presently tested and evaluated.

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References:

[1] EN 1990 *Basis of Structural Design*, Design assisted by testing, CEN Brussels, 2004.

[2] EUR 27666 EN *Prospect for New Guidance in the Design of FRP Support to the implementation, harmonization and further development of the Eurocodes*, European Commission - Joint Research Centre - Institute for the Protection and the Security of the Citizen, 2016, ISBN 978-92-79-54225-1.

[3] A. T. Abdelaziz, R. Boukhili, S. Achiou, S. Gordon, H. Boukehili, Bonded joints with composite adherents, Part I, Effect of specimen configuration, adhesive thickness, spew fillet and adherent stiffness on fracture, *International Journal of Adhesion & Adhesives*, Vol. 26, 2006, pp. 226–236, ISSN 0143-7496.

[4] F. Ascione, Ultimate behaviour of adhesively bonded FRP lap joints, *Composites, Part B: Engineering*, Vol. 40, 2009, pp. 107-115, ISSN 1359-8368.

[5] F. Ascione, Mechanical behaviour of FRP adhesive joints, *Composites, B: Engineering*, Vol. 40, 2009, pp. 116-124, ISSN 1359-8368.

[6] ASTM D5573-99 *Standard Practice for Classifying Failure Modes in Fiber Reinforced Plastic (FRP) Joints*, ASTM International, West Conshohocken, PA, 2012.

[7] M. Štrba, M. Karmazínová, Using of the Design assisted by testing method in case of the experimental verification of the load-carrying capacity of expansion anchors, *International Journal of Mechanics*, North Atlantic University Union, U.S.A., Vol. 10, 2016, pp. 227-234, ISSN 1998-4448.

[8] M. Štrba, M. Karmazínová, Experimental verification of load-carrying capacity in case of steel post-installed expansion anchors subjected to a tension loading, In *Fluids, Heat and Mass Transfer, Mechanical and Civil Engineering - Proceedings of 6th European Conference of Civil Engineering (ECCIE '15)*, WSEAS Press, Budapest, Hungary, 2015, pp. 95-98, ISSN 2227-4596, ISBN 978-1-61804-358-0.

[9] M. Štrba, M. Karmazínová, On the problems of actual behaviour and load-carrying capacity of steel anchor bolts subjected to repeated tension loading, In *Proceedings of 3rd European Conference of Civil Engineering (ECCIE '12) "Recent Advances in Engineering"*, WSEAS Press, France, 2012, pp. 273-276, ISSN 1877-7058, ISBN 978-1-61804-137-1.

[10] M. Štrba, S*teel expansion anchors under cyclic tensile loading*, Editor PhD Thesis, vol. 633, Brno, 2011, ISSN 1213-4198.