Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 172 (2017) 68 – 74

Procedia Engineering

www.elsevier.com/locate/procedia

Modern Building Materials, Structures and Techniques, MBMST 2016

Structural analysis of GFRP truss bridge model

Darius Bačinskas[a], Arvydas Rimkus[a,b,*], Deividas Rumšys[a] , Adas Meškėnas[a], Simas Bielinis[c], Aleksandr Sokolov[a], Tomas Merkevičius[a]

[a]*Department of Bridges and Special Structures, Vilnius Gediminas Technical University, Sauletekio av. 11, Vilnius LT–10223, Lithuania*
[b]*Research Laboratory of Innovative Building Structures, Vilnius Gediminas Technical University, Sauletekio av. 11, Vilnius LT–10223, Lithuania*
[c]*FibroLT Ltd. S. Žukausko str. 17-21, Vilnius LT-08234, Lithuania*

Abstract

Experimental investigation of structural behavior of glass fiber reinforced polymer (GFRP) space truss bridge model subjected to static loading is discussed in this paper. Bridge prototype was assembled using GFRP profiles produced by *Fiberline Composites Ltd*, steel bolts and GFRP brackets. In order to load the structure, wooden bridge deck was installed. Total load of 13.3 kN was applied in four stages while measuring the bridge node displacement. Flexural behavior of the truss structure was monitored at every loading stage. In order to perform the comparison analysis of truss structural behavior, numerical model was created employing finite element software *Solidworks*. Comparative analysis has shown good agreement between experimental and numerical results (the margin of error varied from 0,3 up to 10,5%). The obtained results show, that designed and tested bridge model has a sufficient reserve of structural stiffness. Performed investigation reveals that GFRP profiles are suitable for real pedestrian bridge superstructures.

Peer-review under responsibility of the organizing committee of MBMST 2016

Keywords: GFRP composite; footbridge structures; numerical modeling; static loading; deflection.

1. Introduction

Deterioration and damages due to mechanical loadings and environmental stressors are the most critical issues in maintenance and inspection procedures of existing bridge structures. Replacement and rehabilitation of transportation

* Corresponding author. Tel.: +3-705-274-5246; fax: +3-705-270-0112.
E-mail address: Arvydas.Rimkus@vgtu.lt

Peer-review under responsibility of the organizing committee of MBMST 2016
doi:10.1016/j.proeng.2017.02.018

structures in the United States cost about $5 billion USD per year. Furthermore about 30% of all bridges in United States, i.e. 180,000, are considered structurally deficient or suffering from deterioration and are eligible for funding. Problems caused by physical aging of transport infrastructures initiated research of innovative construction solutions and sustainable development [1].

Application of composite materials, e.g. fiber reinforced polymer (FRP), is one of the potential fields that can be involved in the development of bridge structures. FRPs have appropriate physical and mechanical properties, such as high strength to weight ratio, high impact strength, low electrical and thermal conductivity as well as high durability [2]. These advantages lead to low maintenance cost and longer service life of structures. Composite materials have steadily gained ground in nearly all sectors [3]. Growing application of composites can be explained by better and more comprehensive knowledge of the fundamental properties of composites and their long service life.

During recent decades, FRP materials were used for bridge structures. In most cases, FRP materials are applied as internal [4] or external [5] reinforcement for reinforced concrete members. A number of theoretical and experimental investigations have been carried out for the analysis of FRP bridge decks [6] and superstructures [7]. Recently, some research was dedicated for bridge deck construction using stay-in-place FRP structural forms [8]. Thus, practical experience shows that FRP composites usually are applied in interaction with other materials (i.e. concrete, steel or timber). Stand-alone application for bridge structures are still limited by the FRP characteristics of structural behavior. Moreover, in the calculations of structural response, it is necessary to evaluate the potential of materials aging (degradation), especially in the case of glass fiber reinforced polymer (GFRP) application. Connections and joints between composites are also very important to structural behavior but still requires sophisticated analysis. The investigation of these effects requires detailed and comprehensive experimental study, which will allow to create the constitutive models and design methods for FRP bridges.

Experimental investigation of structural behavior of GFRP truss bridge model under static loading is discussed in this paper. Bridge prototype was assembled using GFRP profiles produced by *Fiberline Composites* [9], steel bolts and GFRP brackets. In order to load the structure, wooden bridge deck was installed. Total load of 13.3 kN was applied in four stages measuring the bridge node displacement. The profiles of bridge model deflections were obtained at every loading stage. In order to perform the comparison analysis of truss structural behavior, numerical model of bridge prototype was created employing finite element software *Solidworks*. Comparison analysis has shown good agreement between experimental and numerical results. The margin of error of deflections at mid-span of the bridge for the maximum load was less than 1%. Further research is needed for the dynamic assessment of FRP truss bridge behavior.

2. Experimental program

Experimental program provided in this paper includes static testing of pedestrian truss bridge model made of GFRP profiles. The length of considered structure was 6 m, width – 0.75 m, height – 0.53 m. The bridge prototype was constructed in the Research Laboratory of Innovative Building Structures in Vilnius Gediminas technical university. The assembly of the bridge model was made using *Fiberline* profiles, steel bolts and GFRP brackets. Mechanical and physical characteristics of pultruded GFRP profiles are provided in Table 1 [9].

Table 1. Mechanical and physical characteristics of GFRP material [9].

Characteristic	Value
Density, ρ	1.8 g/cm^3
Tensile strength, f_t	240 MPa
Compressive strength, f_c	240 MPa
Modulus of elasticity (nominal), E_n	24 GPa
Modulus of elasticity (experimental), E	31.3 GPa
Shear modulus, G	3 GPa
Poisson coefficient, ν	0.23

2.1. Materials

The GFRP pultruded profiles were produced by *Fiberline Copmosites*. While the glass fibers are embedded in a polyester matrix, pultrusion process ensures consistent quality of the profiles in various shapes. In accordance with several tensile tests of GFRP profiles performed by Correia [10], the average tensile and compressive strength is 240 MPa. In order to model actual response of the bridge structure, several supplementary 3-point bending tests of GFRP profiles were performed to determine the modulus of elasticity. It was observed, that the modulus of elasticity varied from 29.7 to 32.8 GPa. Average value of 31.3 GPa was used in further investigation.

2.2. Design of the structure

Figure 1 shows the design, geometry and dimensions of the truss bridge model. The geometry of the bridge specimen was selected regarding lightweight truss design recomendations for short span pedestrian bridges [11]. The prototype was composed according to serviceability requirements and assembled using structural components of 5 shapes: 120×60×6 mm I-profile, 120×50×6 mm U-profile, 50×50×5 mm square tube, 75×75×6 mm angle profile and 70×60×5 mm handrail. The bottom chord beam was realized by two U-profiles coupled by square tube. The connection between the GFRP profiles was made by M8 steel bolts. Floor beam (FB) scheme and typical bolt joints between the composite components are presented in Figure 1a and b, respectively.

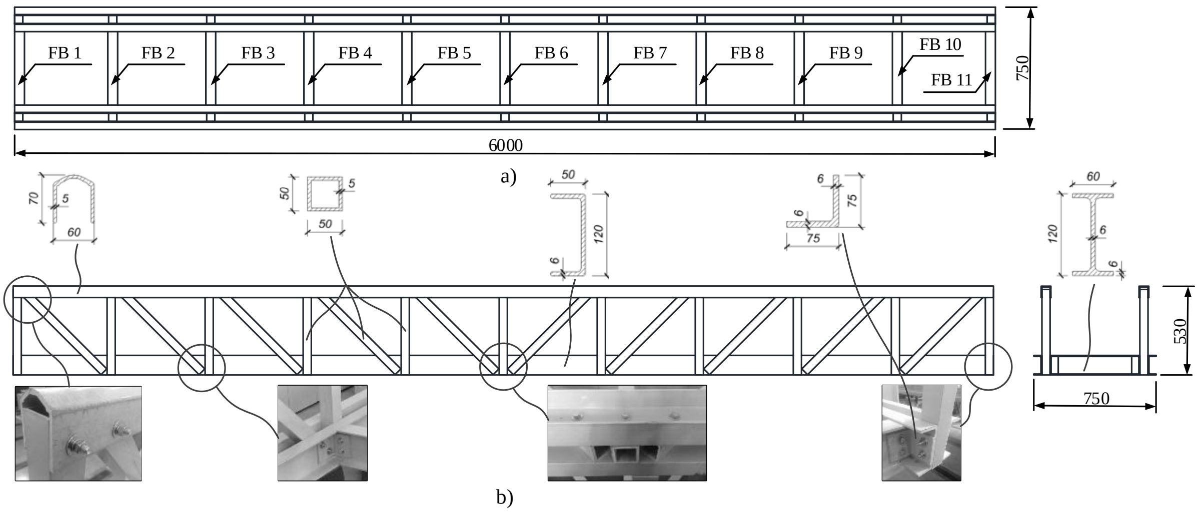
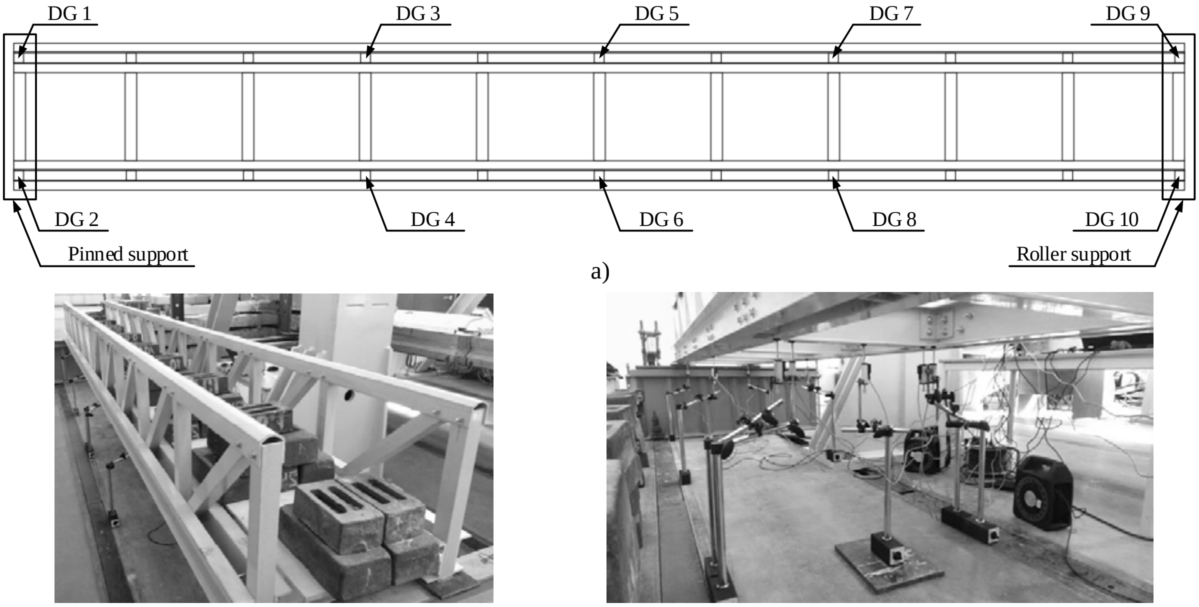


Fig. 1. Floor beam (FB) scheme (a) and typical bolt joints between the composite components (b).

2.3. Instrumentation and test setup

In order to ensure appropriate truss behaviour, bottom chords of the bridge model were equipped with four bearing pads. Next to the first and eleventh floor beams pinned and roller supports were installed bellow the bearing pads, respectively. Linear variable displacement transducers were used as a displacement gauges (DG) to measure the deflections of the bottom chord of the structure. Arrangement of the DG is presented in Figure 2.

To investigate the structural behaviour of the prototype, uniformly distributed load was applied introducing steel bricks of 20-25 kg on the wooden deck panels (see Fig. 2b). The panels were simply supported on the floor beams without causing any restrains to the structure. Uniformly distributed load of 3 kN/m was applied on the central floor beams (FB 2 – FB 10) and 1.5 kN/m – on the side floor beams (FB 1 and FB 11). Loading process was performed in four stages – starting to place the steel bricks on the FB from the pinned support to the roller support. Detailed loading order and total weight on each FB are presented in Table 2.



b) c)

Fig. 2. Arrangement of the displacement gauges (a) and (c); load distribution on a wooden bridge deck (b).

Table 2. Total weight on each floor beam and order of the loading stages.

Floor beam (FB)	1	2	3	4	5	6	7	8	9	10	11
Loading I, kg	70.9	132.9	131.8	-	-	-	-	-	-	-	-
Loading II, kg	70.9	132.9	131.8	132.6	131.0	130.9	-	-	-	-	-
Loading III, kg	70.9	132.9	131.8	132.6	131.0	130.9	131.0	132.5	-	-	-
Loading IV, kg	70.9	132.9	131.8	132.6	131.0	130.9	131.0	132.5	131.8	133.0	71.0

2.4. Experimental results

To assess the flexural performance of the bridge prototype four static loading stages were executed. Table 3 depicts the bridge prototype response to subjected loading. Truss deflections were measured by the displacement gauges positioned on the floor beams described in previous section. The maximum deflection of 6.635 mm was obtained in mid-span of the structure at the IV loading stage. The admissible maximum deflection is equal to 12 mm.

Table 3. Deflections of the truss at every loading stage.

Displacement gauge (*DG*)	1	2	3	4	5	6	7	8	9	10
Loading I, mm	-0.045	-0.049	-0.747	-0.803	-0.741	-0.847	-0.176	-0.607	-0.036	-0.037
Loading II, mm	-0.179	-0.193	-2.954	-3.182	-3.120	-3.695	-2.339	-2.663	-0.142	-0.162
Loading III, mm	-0.260	-0.276	-4.279	-4.552	-5.070	-5.574	-3.927	-4.408	-0.238	-0.268
Loading IV, mm	-0.302	-0.322	-4.972	-5.300	-6.107	-6.635	-5.044	-5.514	-0.260	-0.335

3. Numerical analysis

3.1. Numerical model

The behavior of the pedestrian bridge was simulated using the SolidWorks software. Geometry, support and loading conditions of numerical model was based on the experimental bridge prototype (see 2.1-2.3 sections). For the permanent load, the deadweight of the wooden deck and GFRP profiles were considered. Curvature-based mesh parameter (maximum element size 20 mm, minimum – 4 mm) was selected for this model. Components of the model were joined using pin connectors which represents bolt joints (Fig. 3). Pin connectors allows to reduce the number of finite elements in the connection zones. The GFRP profiles were simulated assuming the linear elastic behavior. All static calculations were made using FFEPlus (iterative) solver. In the following section the influence of material parameters on the structural behavior is analyzed.

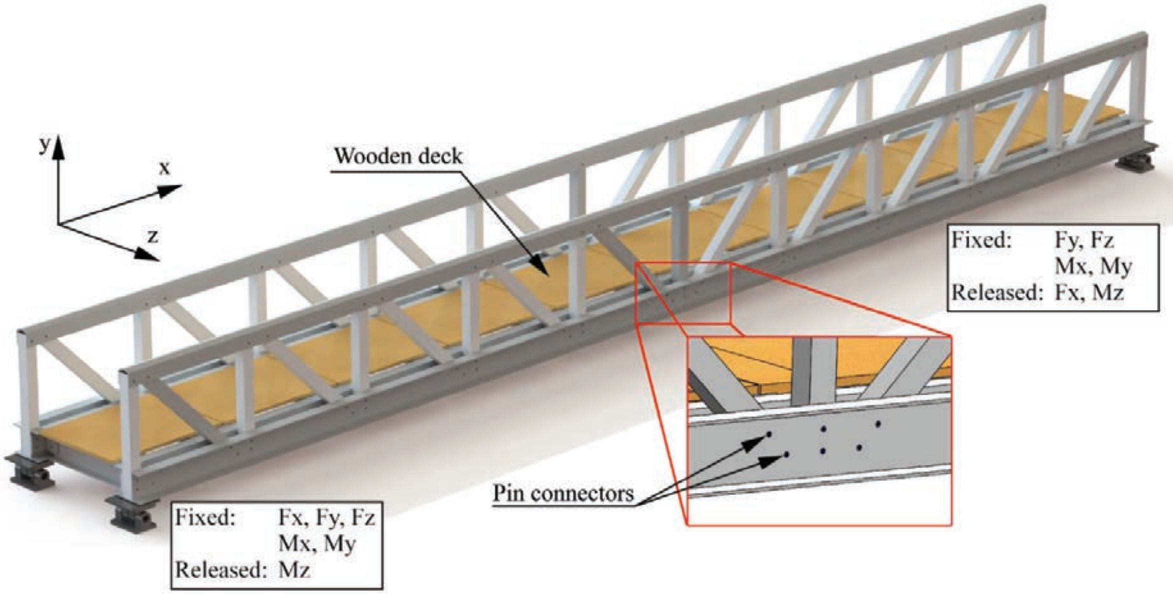


Fig. 3. Numerical model of the truss bridge.

3.2. Analysis results

The numerical modeling was performed on a basis of Young's modulus variation. As a reference, average value of minimal ($E_{obs,min}$=29.7 GPa) and maximal ($E_{obs,max}$=32.8 GPa) experimental modulus of elasticity was selected – $E_{obs,avg}$=31.3 GPa. Numerical modeling results were compared with experimental data. Numerical and graphical deflection comparison is presented in Table 4 and Figure 4, respectively. Moreover, numerical modeling was performed using nominal modulus of elasticity $E_{nom,k}$=24.0 GPa (reffered by producer) and compared with experimental results.

Figure 4 illustrates that the deflection obtained from numerical simulation, which employes the $E_{obs,avg}$ value, is in a good agreement with experimental results in all loading stages. The margin of error varies from 0,3 up to 10,5%. At maximum loading (IV loading phase) margin of error accounts for only 0,3%. In case the nominal value of Young‘s modulus is considered ($E_{nom,k}$), the error of deflection increases up to 29,3-43,9%. This indicates that the manufacturer of GFRP profiles declares precautious (conservative) value of the modulus of elasticity and significantly increases the reserve of the structural stiffness. Relative deflections of the bridge model were obtained as L/942 (for the experimental model), L/944 (for the numerical model, considering $E_{obs,avg}$ value) and L/728 (for the numerical model, considering $E_{nom,k}$ value). Here L is the length of the structure. It is important to note, that the limit of the relative deflections of pedestrian bridges is not regulated according to EN standards. However, according to the requirements of other design standarts [12], the limit value of relative deflection is specified as L/400.

The obtained results show, that designed and tested bridge model has a sufficient reserve of structural stiffness. Furthermore, the adequacy of numerical modeling was confirmed by excellent agreement between theoretical and experimental deflection results. Performed investigation reveals that GFRP profiles are suitable for pedestrian bridge structures.

Table 4. Experimental and theoretical deflection results.

Loading stage	Maximal deflection Δ, mm					Δ_{Th}, $E_{obs,avg}/\Delta_{Exp}$	Δ_{Th}, $E_{nom,k}/\Delta_{Exp}$
	Δ_{Exp}	Δ_{Th}, $E_{obs,min}$	Δ_{Th}, $E_{obs,avg}$	Δ_{Th}, $E_{obs,max}$	Δ_{Th}, $E_{nom,k}$		
I	-0.794	-0.875	-0.832	-0.794	-1.080	1.048	1.360
II	-3.407	-3.958	-3.765	-3.590	-4.882	1.105	1.433
III	-5.322	-5.822	-5.538	-5.281	-7.182	1.041	1.349
IV	-6.371	-6.680	-6.354	-6.058	-8.239	0.997	1.293

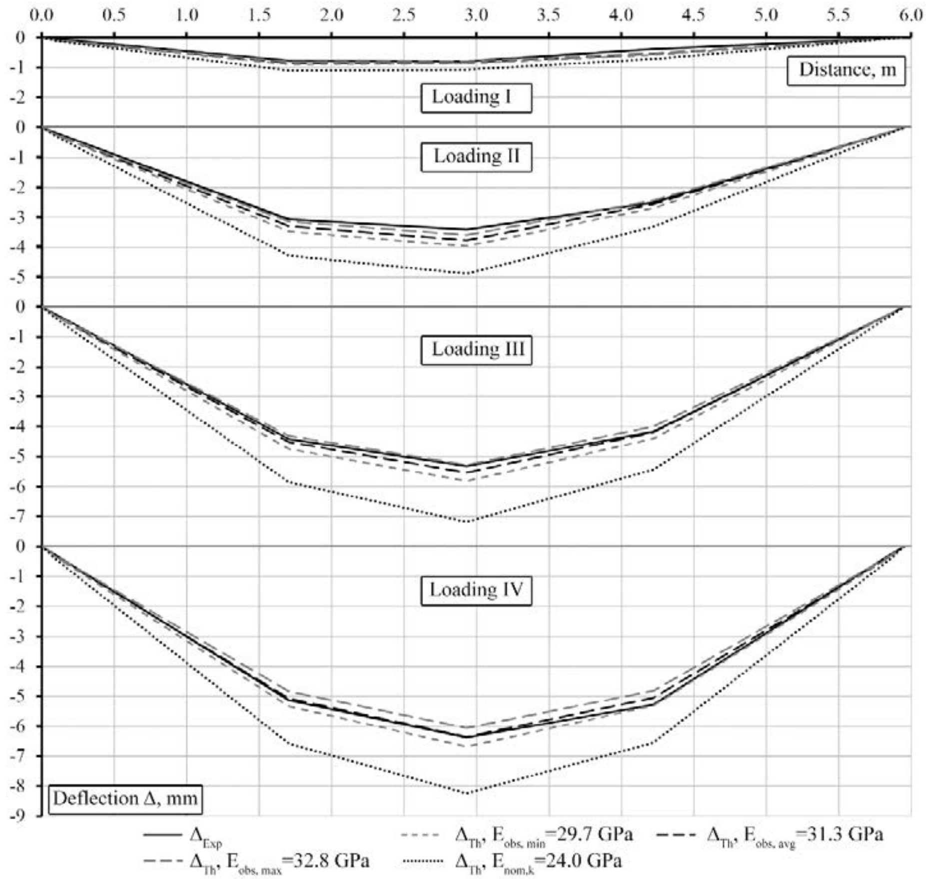


Fig. 4. Deflection profiles of GFRP truss bridge subjected to different static loading stages.

4. Concluding remarks

This paper presents the experimental investigation of pedestrian bridge model made of GFRP profiles. Bridge prototype was tested under four static loading stages (the maximum load of 13,3 kN). Load value has been selected as 5 kPa, in accordance with pedestrian bridge design regulations. Deflections of the bridge were monitored at every loading stage in 10 bridge nodes. In order to compare experimental and theoretical results, numerical model was developed employing CAD software SolidWorks. Analysis has shown that the manufacturer of GFRP profiles declares precautious (conservative) value of the modulus of elasticity which results in higher structural stiffness. In case the nominal value of Young‘s modulus is considered ($E_{nom,k}$), the error of deflection reaches 29,3-43,9%. At maximum loading (IV loading phase) margin of error accounts for only 0,3%, considering experimentaly attained $E_{obs,avg}$ value. Performed investigation reveals that GFRP profiles are suitable for real pedestrian bridge superstructures. Further research is needed for assessment of dynamic behavior as well as long-term effects of GFRP composite bridges.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Research Council of Lithuania (Research project No. MIP-093/2015). The authors wish to thank *Fiberline Composites A/S* for providing structural profiles and *FibroLT Ltd.* for technical support. Technical assistance provided by MSc student T. Dulskas during the preparation of the pedestrian truss bridge model is greatly acknowledged.

References

[1] D. M. Frangopol, M. Liu, Multiobjective optimization for risk-based maintenance and life-cycle cost of civil infrastructure systems, in: IFIP International Federation for Information Processing, Vol. 199, System Modeling and Optimization, eds. F. Ceragioli, A. Dontchev, H. Furuta, K. Marti, L. Pandolfi, Springer, Boston, 2006, pp. 123-137.

[2] C. E. Bakis, L. C. Bank, V. L. Brown, E. Cosenza, J. F. Davalos, J. J. Lesko, A. Machida, S. H. Rizkalla, and T. C. Triantafillou, Fiber-reinforced polymer composites for construction – state-of-the-art review, Journal of Composites for Construction 6(2) 2002 73-87.

[3] E. Gudonis, E. Timinskas, V. Gribniak, G. Kaklauskas, A. K. Arnautov and V. Tamulėnas, Fiber-reinforced polymer composites for construction – state-of-the-art review, Engineering Structures and Technologies 5(4) 2013 147-158.

[4] V. Gribniak, A. K. Arnautov, G. Kaklauskas, V. Tamulėnas, E. Timinskas, A. Sokolov. Investigation on application of basalt materials as reinforcement for flexural elements of concrete bridges, Baltic Journal of Road And Bridge Engineering10(3) 2015 201-206.

[5] M. Aktas, Y. Sumer, Nonlinear finite element analysis of damaged and strengthened reinforced concrete beams, Journal of Civil Engineering and Management 20(2) 2014 201-210.

[6] P. Kumara, K. Chandrashekharaa, A. Nanni, Structural performance of a FRP bridge deck, Construction and Building Materials 18 (2004) 35-47.

[7] Hsiao-Hui Hung, Yu-Chi Sung, Kou-Chun Chang, Shih-Hsun Yin, Fang-Yao Yeh, Experimental testing and numerical simulation of a temporary rescue bridge using GFRP composite materials, Construction and Building Materials 114 (2016) 181-193.

[8] M. Noel, A. Fam, Design equations for concrete bridge decks with FRP stay-in-place structural forms, Journal of Composites for Construction, 2016, DOI: 10.1061/(ASCE)CC.1943-5614.0000681, (accepted for publication).

[9] Fiberline Composites A/S, Fiberline Design Manual, Kolding, 2014.

[10] Correia, J., Cabral-Fonseca, S., Branco, F., Ferreira, J., Eusébio, M. I., & Rodrigues, M. P. (2005, July). Durability of glass fibre reinforced polyester (GFRP) pultruded profiles used in civil engineering applications. In Proceedings of the 3rd International Conference on Composites in Construction (pp. 11-13).

[11] Bernard Potyrala, P. (2011). Use of fibre reinforced polymeromposites in bridge construction. State of the art in hybrid and all-composite structures.

[12] SP 46.13330.2012. Bridges and pipes. Set of design rules. Ministry of Regional Development of Russian Federation, 2012. (in Russian).