

MATERIAL AND PERFORMANCE RESEARCH ON THE FRP COMPOSITE BRIDGE GIRDER

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This paper is devoted to the use of FRP composites to built durable and reliable footbridges. The objective of this paper is to disseminate results of the research project for the development of the FRP based solution for pedestrian bridges. It shows material testing, planning design and FEM analysis of the proposed solution as well as model testing procedure to be undertaken for checking static and dynamic performance of FRP composite girder.

Key words: FRP composites, bridge girder, footbridge, material test, loading test.

Розглянуто використання FRP композитів для будівництва міцних та надійних пішохідних мостів. Подано результати дослідницького проекту з розробки пішохідних мостів з використанням FRP, а також результати випробувань матеріалів, планування та МКЕ аналіз пропонованих рішень та моделі для перевірки поведінки FRP при статичному та динамічному навантаженні.

Ключові слова: FRP (полімер, армований фібрами) балка моста, пішохідний міст, випробування матеріалів, випробування під навантаженням.

Introduction

When the phases consist of a fibrous material dispersed in a continuous matrix phase, the resulting composite material is commonly known as Fibre Reinforced Polymer (FRP). FRP composites offer the designer a combination of properties not available in traditional materials (concrete, steel and wood) and are being commonly applied in industries like aerospace, automotive and naval. Nowadays we have also huge development of FRP composites in civil engineering, particularly in bridge maintenance and construction. FRP composites are commonly used for strengthening of existing structures in concrete, steel and timber. The first application of FRP's for bridge structural reinforcement took place in Ibach, Switzerland, in 1999 [1]. Since that time this technology has been commonly developed all over the world. In the last years there has been a concerted effort to migrate FRPs into the construction industry for use in primary load bearing applications. Recently FRP composites are used more and more in new construction structural components thanks to their advantageous material properties [2]. However, potential capacity of FRP materials is not yet been exploited widely because of lack of specific codes for design (f.e. Eurocode for FRP composites in construction). This implies reluctance of the clients as a public administrations to accept these materials and lack of confidence of structural bridge designers in the use of these materials as they are not guaranteed by a legal codes. There is a need for more practical applications and real examples of FRP's being used so the material itself is well accepted by the industry and clients.

It is worthy to mention the development in this field, done by Spanish construction company *Acciona Infraestructuras*, which is the business partner of *Mostostal Warszawa S.A.* One of the latest pedestrian bridge designed, manufactured and built by *Acciona* was the Almuñécar footbridge built in Madrid in 2010 [3], which replaced an existing reinforced concrete footbridge crossing the Manzanares river (Fig.1a,b). It has a span of 44 m, a width of 3,5 m and it is formed by a single FRP composite girder with a linear piece-wise axis and an inverted "Ω" cross section. The girder, completely made of carbon fibre epoxy composite, presents a series of longitudinal and transversal stiffeners to be able to accomplish with the challenging architectural requirements: a girder with a depth not greater than 1,20 m. The girder, together with its longitudinal stiffeners, was manufactured by resin infusion in one shot. The girder's transversal stiffeners were instead produced separately and joined to the outer surface of the girder by adhesive [4].



Fig. 1. (a) Installation of the FRP girder; (b) View of the Almuñecar footbridge (Courtesy of Acciona Infr.)

The experience gained in the construction of the Spanish footbridge [5] has been further explored in the research project realized by the science-business consortium conducted by *Mostostal Warszawa S.A.* The main goal of the project was to develop and demonstrate technologies for FRP pedestrian bridges including material research, concept design, manufacturing techniques and large scale testing as well as the first implementation of an idea. The research project has been partially financed by the National Centre for Research and Development in Poland. This paper describes some of the project' main results obtained during the research carried out with the close cooperation with the Rzeszow University of Technology, Road and Bridge Department.

Research on materials selection for FRP composites

At the early stage it has been decided, based on previous experiences that the manufacturing technique that was going to be applied in the footbridge production will be VARTM (vacuum assisted resin transfer moulding). The reason for that was mainly low cost investment in initial equipment, possibility and previous experiences in large scale elements – close to bridge sections scale (e.g. large scale boats, windmill structural elements) and material accessibility. After taking this decisions next steps were taken and the one of which was a selection of materials to be used.

In order to obtain the material properties database needed for future analysis and design there has been carried out comprehensive material research. This material research was conducted by the partners of project consortium: *Materials Engineers Group Sp. z o.o., Warsaw*, and the Warsaw University of Technology, Materials Science Department. Three types of fibres were selected (glass, carbon and basalt) from different manufacturers. Aramid fibres (Kevlar) were excluded at the initial stage of research basing on literature study only. The main reason for that was relatively low properties comparing to carbon fibres and high price. After the first series of testing campaign basalt fibres were also excluded due to the low benefits obtained comparing to glass fibres and much higher cost as well. Finally, the decision was taken to use carbon fibre and E-glass fabrics manufactured by Japanese company *Toray Industries*. Various resins systems were also selected for further testing in order to select the optimum product. The system Huntsman Araldite epoxy resin and hardeners LY1564 XB3487 and XB3486 were selected as the best performance solution. The criteria to be taken into account when evaluating basic composite products were: strength, viscosity, curing time (so-called pot life) as well as toxicity and market price.

The comprehensive material research in order to obtain mechanical properties (R_m , E , G , ν) were conducted for two types of epoxy laminates, based on carbon and E-glass fabrics and manufactured using formerly assumed resin infusion process:

- L1 – the laminate with 3 layers of unidirectional carbon fabrics with 600 g/m² unit weight,
- L2 – the laminate with 3 layers of E-glass fabrics ($\pm 45^\circ$) with 1200 g/m² unit weight.

As mentioned before, the laminates were made using the targeted infusion process (VARTM). The vacuum during the process was about 30-60 hPa. Finally infused plate elements were cured at 70 °C for 4 hours. In order to assess reproducibility of material parameters, the laminates were produced in

9 independent series of samples for both types of composites (carbon and glass) in the subsequent infusion process. Based on testing campaigns it has been created the database of material properties, that have been used later on for numerical analysis of the footbridge structural members. The average material parameters of two laminates are shown in Table I.

Table I

Average values of basic material properties for the composite L1 and L2

Laminate	R_m [MPa]	R_c [MPa]	E_x [GPa]	E_y [GPa]	G [GPa]	ν
L1 (carbon)	1270	360	125,0	8,0	4,00	0,31
L2 (glass)	450	280	24,0	24,0	4,37	0,14

The E-modulus values are very close to the literature ones assumed in initial footbridge girder calculations. The carbon laminates (L1) properties have not reached literature values and are much lower than theoretical ones. This discrepancy is due to the fact, that the test specimen was taken from the laminates produced as part of a large-scale elements, made in industrial conditions and taking into account the difficult process of carbon fabrics infusion. The obtained results allow to give a positive assessment in materials properties repeatability and quality of infusion (VARTM). The researchers have reached almost no influence of the changing conditions (temperature, humidity, etc.) during the manufacturing of laminates for its material properties, obtaining maximum repeatability of the process of infusion. This stage of research project allowed to select most adequate composites structure, to determine basic material properties of chosen composites as well as to established the reliable manufacturing process. All these achievements let to start final girder design and its manufacturing.

Footbridge design and girder manufacturing

The typical footbridge to be elaborated and implemented in the frame of the project is to be built with two box FRP composite girders and the sandwich deck panel supported on them and connected to its upper flanges. The basic structural element of the footbridge is a main box girder, designed as a thin-wall trapezoidal open section beam with 1,6 m width, 1,065 height and theoretical span of 25,0 m (Fig.2). In the upper and lower flanges were made of carbon laminate (L1), used with the main purpose of taking main tensile and compressive inner forces in the section. Both side webs as well as deck plate were designed as sandwich sections with outer glass laminates (L2) and PVC foam as a core. The entire girder structure has been stiffened with internal diaphragms and external ribs glued to the girder' outer skin and made of FRP composite as well.

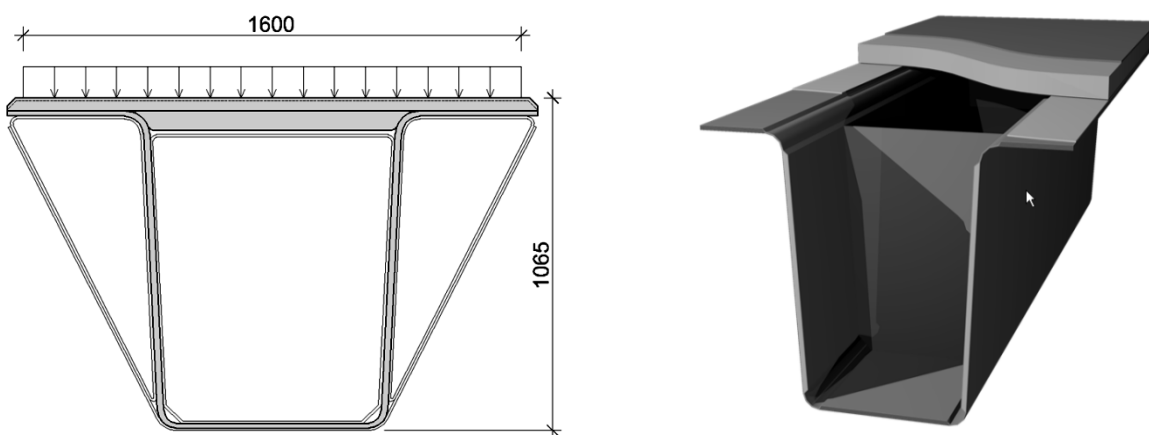


Fig. 2. FRP composite girder cross-section and general layout

The design and optimization process during the initial numerical FEM analysis of the girder was to determine the minimal number of layers for both carbon and glass laminates and thickness of a foam core in webs and deck sandwich elements. Very important design case was to determine the number of internal diaphragms and external ribs, that had to be applied to give additional stiffness of thin wall sandwich webs.

For the purpose of full scale girder testing there has been designed a reduced scale prototype beam with the total length of 13,5 m and with theoretical span in-between supports of 12,0 m (Fig.3). The total weight of the prototype is 4460 kg, where 2100 kg is the weight of concrete poured in one of the support regions. The use of concrete shall answer the necessity of additional stiffening for highly shear loaded support sections as well as the influence of concrete block to enhance the dynamic properties of the girder. The other support region is made totally of FRP composite and has a empty box section structure, stiffened by the diaphragms and ribs only.

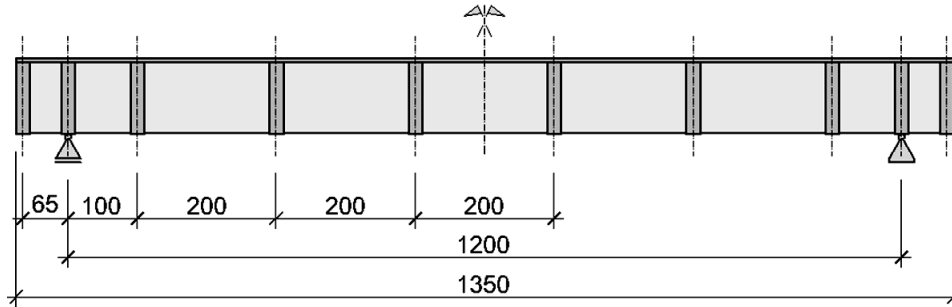


Fig. 3. Prototype girder for full scale testing

All structural members of the girder were manufactured with VARTM process. In this process all dry layers of reinforcing fabrics including PVC foam core are being laid over the mould including linear pipes (resin inlet and air outlet) as shown on the scheme (Fig.4). The manufactured element is covered with vacuum bag foil which is tightly sealed along the mould perimeter. The next step of the process is to remove all air with application of the vacuum pump. Then resin mix (resin + hardener) is being sucked into the element filling all spaces where air was removed with resin mix.

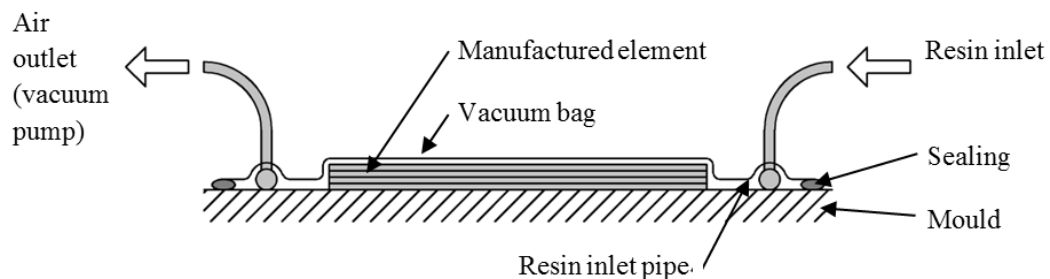


Fig. 4. VARTM– vacuum assisted resin transfer moulding process scheme

With this technique all elements of prototype beam was manufactured including main girder, internal and external diaphragms and ribs as well as sandwich deck panels. Diaphragms were made in two symmetrical parts and then were glued together before assembling them into the beam with use of epoxy adhesive. The infusion process of elements and the prototype beam is shown in Fig.5 and 6.



Fig. 5. Infusion process used for manufacturing of diaphragms and ribs (Mostostal workshop)

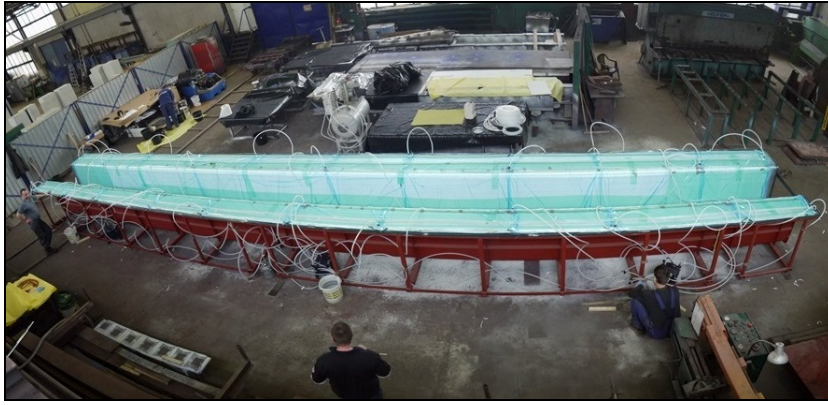


Fig. 6. VARTM process used for manufacturing of the prototype girder (Mostostal workshop)

After being completed in *Mostostal* workshop in Warsaw, the testing girder has been carried with the truck to the structural laboratory of RUT (Fig.7).



Fig. 7. The completed testing girder

FEM numerical analysis before testing

The one of the most important goals of the research project was to build and validate the detailed FEM model of the girder. The model is planned to be used to analyze parametrically the structure including footbridge design assumptions and to optimize its structural framework. To follow the numerical analysis it has been used the finite element modelling environment *SOFiSTiK* 2010. The four-node plate finite elements (quad) were mainly used for girder discretization. Only the concrete filling in the support region has been modelled using brick elements. The entire beam model consisted of 4744 nodes with 7390 plate and 600 brick finite elements. The visualization of the numerical model is shown in Fig.8.

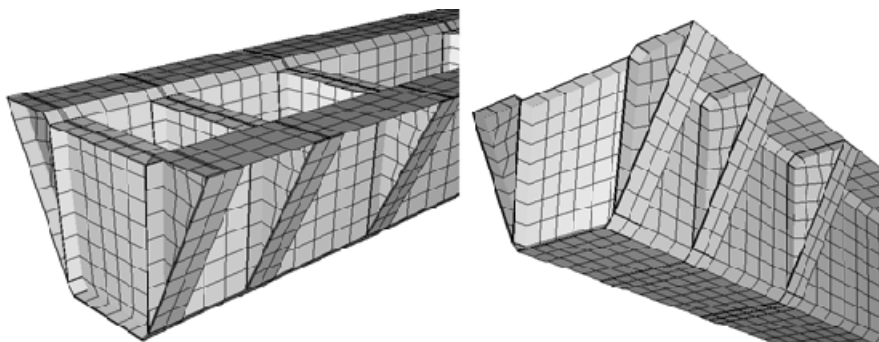


Fig. 8. FEM model of the prototype girder

Material properties obtained from the testing (for carbon and glass laminates, foam core and concrete) were used in FEM modelling. The orthotropic properties of the laminates having different properties in different directions of fibres was also taken into account. Thanks to software code possibilities, the exact layer structure of the laminates could be discretized and till 10 various layers (means: fabrics) were described in plate finite elements. Thus enabled the exact material properties to be assumed in the girder model with a combination of three basic materials: carbon and glass laminates and core foam.

It was assumed, that loading would be realized following the regular rules of 4 point bending test as shown in the scheme (Fig.9). Two point loads will be distributed on the contact surfaces with the width equals 1,6 m (as for the deck) and the length of 0,30 m each. The maximum load for each point (630 kN) was established according to the capacity of the load testing machine being available at the RUT structural laboratory. To be close as much as possible to real load condition, the loading was also modelled in this manner in numerical analysis.

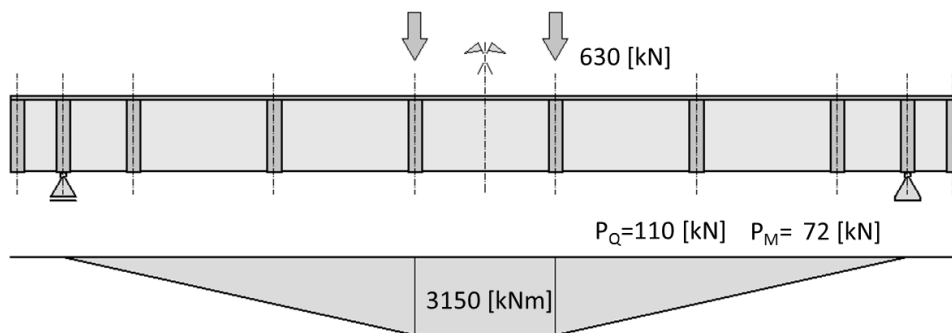


Fig. 9. Four – point bending scheme for prototype girder testing

The numerical model of the girder was used for the second-order static and dynamic analysis under loading conditions assumed for testing. The foreseen static behavior of the girder under assumed load is shown in Fig.10, where the relation of P-delta for the middle section of the girder has been plotted. As can be easily seen in this plot, the static performance of the girder will be linear elastic in the full range of assumed loading. No local failures was also discovered within FEM model under this loading. The strength and stability of each girder section were numerically revealed and thus confirmed the proper design and appropriate structure framework of the girder and entire footbridge as well.

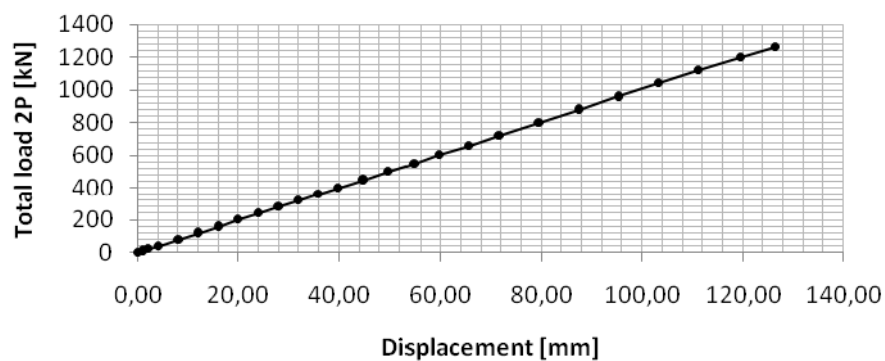
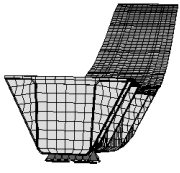
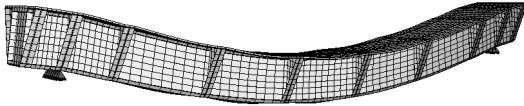
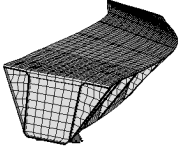
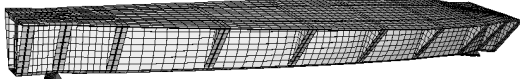
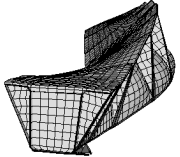
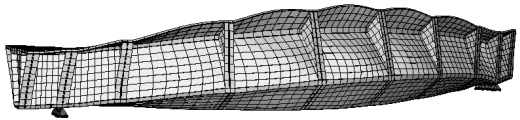


Fig. 10. The P-delta plot for the girder determined in FEM analysis

The elaborated FEM model was also used for prediction of theoretical values of girders' self-frequencies, damping parameters and modes of vibrations. The first three self-frequencies and corresponding vibration modes of the girder are shown in Table 2. The comparison of theoretical values determined in FEM analysis with the values obtained in the real test in the laboratory will be one of the main goals of the ongoing research. When the FEM model of the girder is validated against the test values, it will be used for girder's structural optimization and detailed designing of the footbridge.

Three self-frequencies and corresponding vibration modes of the girder

No.	Modes of vibrations		Self-frequency [Hz]
	Transversal	Longitudinal	
1.			16,3
2.			17,8
3.			26,8

Prototype girder testing under static load

The main objective of prototype girder testing is to evaluate its behaviour under static load and to determine its real carrying capacity, modes of failure as well as basic dynamic parameters. The first step is to check the girder performance under the standard pedestrian load according to Polish code for footbridges. On this stage also the validation of FEM model for design purposes will be undertaken. The initial static tests will be followed by dynamic (modal) tests of the girder. The main results of these tests will allow to establish the main dynamic characteristics of tested element, i.e.: self-frequencies and corresponding modes, logarithmic decrement of damping, dynamic factors for footbridge and the level of vertical accelerations. Owing to these results the comfort criteria of the footbridge will be checked and adjust if needed. Modal tests will be carried out in the scheme of SIMO test (single input multiple output). Finally, the girder will be loaded with quasi-static loading until failure. The ultimate carrying capacity and modes of failure will be the most interested output to be obtained at this stage of research.



Fig. 11. The prototype girder at the testing stand in structural laboratory of RUT

During the static and failure tests there have been applied about 50 strain gauges including 10 rosette gauges that will enable to measure the principal stresses in the middle section of the girder. Besides 5 displacement inductive transducers will be used to observe girder behaviour under static load. The modal hammers and electrodynamic exciter will be used for girder excitation. Dynamic response will be measured using a set of accelerometers as well as displacement transducers. With the results of structural acceleration in individual measuring points it will be possible to determine the vibration modes for the first few self-frequencies of the girder and already mentioned dynamic parameters.

The comprehensive laboratory tests of the girder model have just started at the structural laboratory of the RUT (Fig.11). The final results of the tests will be presented at the conference.

Final conclusions

The output of research project presented in this paper gives a very promising future for FRP materials applications in bridge engineering. The proposed manufacturing techniques (VARTM) can be successfully applied in large scale bridge girders taking into account laminate thicknesses reaching till 2 cm. However, in order to be more competitive with elaborated technologies, there is a strong need for more further research and demonstration in large scale projects.

Large testing plans presented in this paper will give significant answers to the researchers about design rules when it comes to Ultimate Limit State (ULS) and Serviceability Limit State (SLS). Moreover, there will still be a need to test the long term behaviour of this kind of structures as well as its real behaviour under the pedestrian loading. These tests are planned to be carried out in the next stages of the aforementioned research project.

The initial market research undertaken by the authors mainly among public investors (road and railway administrations) confirmed the need on robust, reliable and durable pedestrian bridge concepts, which is very promising when it comes to business exploitation of the project results.

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