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A Polish approach to FRP bridges

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Abstract

The paper presents initial results of a new approach to FRP composite bridge construction that is presently being developed and tested in Poland. The concept combines lightweight concrete with FRP composites to create a durable highly optimised structure. The paper describes the bridge system itself and presents the research results on its development. The basic design is presented together with research results on its development: FEM analysis and a range of static test results of full-scale bridge beam experiments. The paper finishes with some test results of a full scale bridge that was constructed near Rzeszow in December 2015.

Key words: FRP composites, bridge, hybrid structure, FEM analysis, testing, construction

1 Introduction

The heavy traffic on major roads and ageing of the highway infrastructure have led to an increasing demand for new technologies in bridge engineering. Due to their corrosion resistance, high strength and low self-weight, fibre-reinforced polymers (FRP's) offer promising options. FRP composites have become an integral part of the construction industry because of their versatility, high strength-to-weight ratio, enhanced durability, resistance to fatigue and corrosion, accelerated construction and lower maintenance and life-cycle costs. Advanced FRP composite materials are emerging for a wide range of civil infrastructure applications. These include everything from bridge girders and decks, bridge repairs and strengthening, seismic retrofit to marine waterfront structures and sustainable energy-efficient housing. Bridge engineering applications began in the 1980s with research on strengthening of bridges with carbon fibre-reinforced polymer (CFRP), and the construction of the first FRP road bridge in China. More recently, smaller pedestrian and road bridges, bridge decks for new and rehabilitated structures, bridge enclosures and other structural applications have been undertaken using FRP composite components. But there exist only very few FRP bridges that are suited for the heaviest traffic load classes [1].
However, all-composite structural bridge systems have specific shortcomings such as high initial costs, low stiffness (when glass fibre reinforced polymer GFRP is used) and existence

of brittle failure modes. To make the best use of FRP materials and overcome the above drawbacks, combinations of FRP and conventional materials have recently been investigated by a number of researchers [2,3]. According to them the most effective use of FRP composites in structural applications is in the form of a hybrid construction with concrete. The results obtained from the experimental data and analyses show that it is possible to design and manufacture a hybrid FRP composite - concrete beam with adequate stiffness and still achieve the most sought after "pseudo-ductile" behaviour necessary for bridge structures. To address the inherent lack of stiffness of hybrid beams, the FRP laminate is not designed to fail first to give a warning of imminent failure. Instead, its primary role is to provide the required stiffness for the girder. Therefore, the stiffness of the beam can be tailored. The warning of imminent failure is hoped to be achieved through the crushing of concrete. Moreover, the existence of composite action between the concrete and the FRP girder was reported as a serious advantage of these sections. The review of various FRP-concrete hybrid beam or deck systems and their applications in bridge engineering are presented and several problems in future research are discussed in [4].

The main goal of the R&D project was to develop and demonstrate the first Polish FRP composite road bridge, suited for the heaviest traffic load classes. The innovative hybrid idea of a FRP composite – concrete bridge system has been proposed. The paper describes the bridge system itself and presents the research results on its development. The finite element method (FEM) analysis, some research results on the bridge system and demonstrative bridge construction have been briefly presented.

2 Bridge description

The first Polish FRP road bridge is situated in southeast part of Poland, near Rzeszow, along the local road over the Ryjak River. Its nominal carrying capacity is 40 tonnes according to the Polish bridge standard. This is a 22.0 m long single-span simple supported bridge with 10.5 m wide deck carrying 2 × 3.5 m wide roadway and 1 × 2.0 m wide sidewalk. The bridge superstructure is formed by four FRP composite girders with overlying 0.18 m thick concrete slab (Fig. 1).

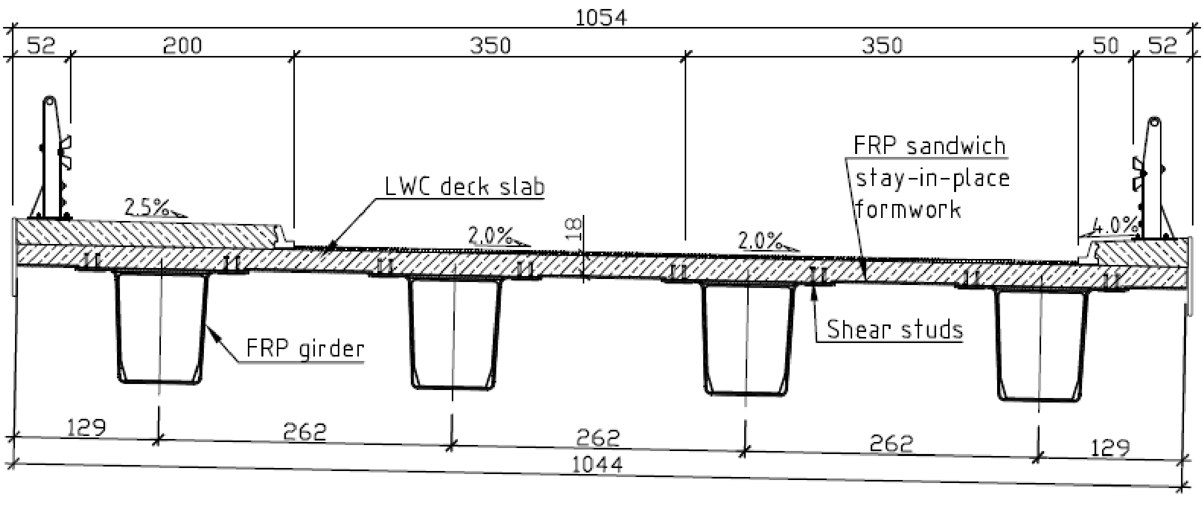

Figure 1: Cross-section of the bridge superstructure (units: [cm])

The FRP girders have a U-shape cross-section with slightly inclined webs, maximum width of 1550 mm and depth of 1020 mm. Each top flange is 350 mm wide and the bottom flange of the box is 735 mm wide. The top flanges and the webs have a thickness of about 28 mm and 23 mm respectively, while the bottom flange is 20 mm thick. The FRP laminates which form the walls of box-girders are made of epoxy resin matrix and hybrid glass-carbon fibre reinforcement. E-glass and carbon fibres in the form of stitched fabrics were chosen as the reinforcement of laminates. The top flanges are made of GFRP and the bottom flange has a hybrid CFRP/GFRP structure. The webs are made as a sandwich panels with 15 mm thick foam layer in between two GFRP laminates.
To increase the torsional stiffness of the girder and to prevent buckling of its webs, six internal diaphragms are placed along the length of the girder. The diaphragms are built as sandwich panels with a structure similar to webs. Similar sandwich panels are also bonded to the top flanges of the girder to be used as a stay-in-place formwork during concrete slab casting. The concrete deck slab is made of lightweight concrete LWC 35/38, reinforced with two layers of 12 mm GFRP rebars. The GFRP rebars were used to enhance the slab durability. The slab is connected to FRP girders through galvanized steel shear connectors which are welded to small steel plates and fastened to top flanges with adhesive.
Finally, the support zones of the FRP girders are filled with concrete to form support cross-beams and to ensure transverse stiffness of the whole span. Steel shear connectors fastened to the webs inside boxes are used to create a composite action between the FRP composite and concrete in the support zones. The deck equipment consists of two concrete sidewalk slabs with safety barriers, polymer curbs, conventional insulation and stone mastic asphalt (SMA) pavement layers, drainage and expansion joints. The reinforced concrete (RC) abutments are founded on 10 continuous flight auger (CFA) piles with 0.60 m diameter and 5.0–7.0 m length. Four elastomer bearings are used to support the span on the abutments.

3 The structure of FRP composite girder

The girders are made of GFRP and CRPP laminas and PVC (polyvinyl chloride) foam in webs (Fig. 2). The top flanges of the FRP box consist of 32 laminas (layers) with mainly one-directional E-glass fibres with 0 orientation (to girder longitudinal axis).
The hybrid bottom flange is formed by 28 carbon and glass laminas in the proportion of 60:40. The number of carbon fibre laminas was selected according to FEM analysis to ensure the required strength and stiffness of the most loaded girder. The sandwich webs consist of 10 layers of bi-directional E-glass fibres and a 15 mm PVC foam layer in between. The foam was used to limit the total volume of glass fibres, and to enhance the shear strength of webs and their multi-directional buckling capacity. The GFRP web laminas are extended towards top and bottom flanges to reinforce the concave arches of the girder and to enable transfer of shear forces as smooth as possible. The same structure as the webs is used in the inner diaphragms with eight layers of bi-directional E- glass fibres with ±45° orientation and a PVC foam layer in between with a total thickness of 30 mm.
The mechanical properties of all laminas were determined by the tensile tests. Using the classical laminate theory and starting from the experimental characterization of the unidirectional laminas and selected laminate stacking sequences, the final material properties of FRP composites (laminates) were established and taken into account in the FEM analysis.

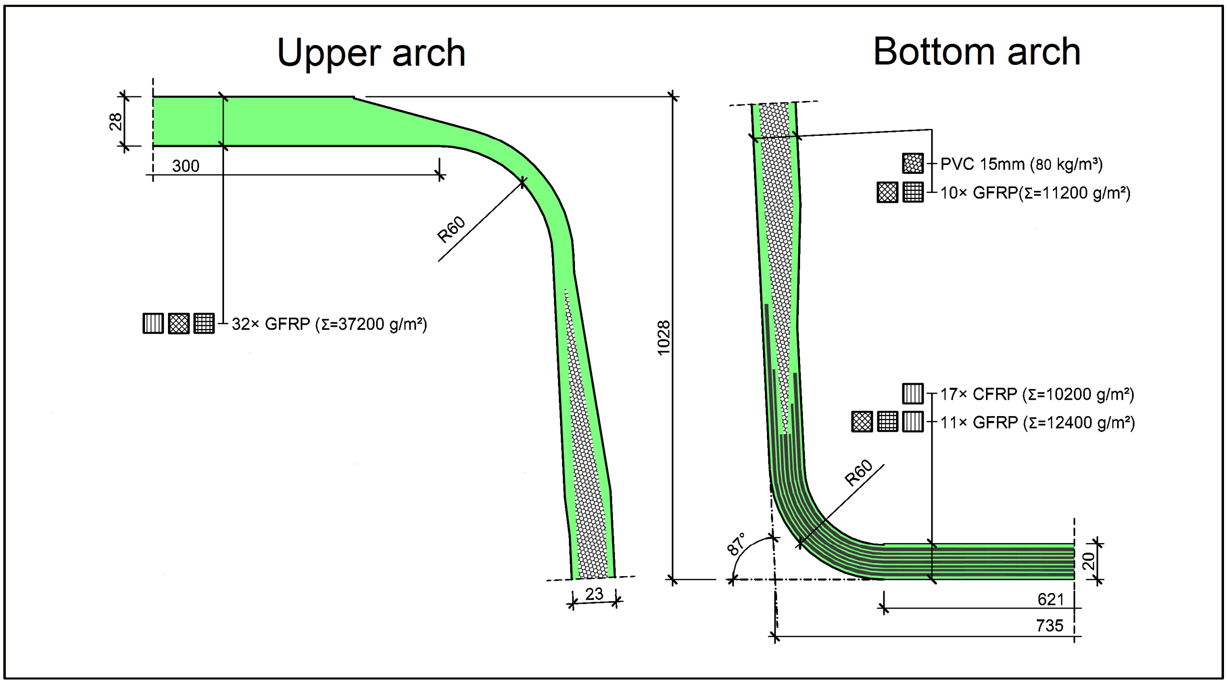

Figure 2: Composite structure of the girder shell

4 FEM analysis and bridge design

Two detailed FEM's (the girder and the superstructure) were prepared in order to use them in the design process of the bridge and to analyse the bridge girder and superstructure behaviour in the different stages of bridge construction and during its service. These models were also used to analyse the girder parametrically in order to optimize its structural framework and to check code requirements. The four-node shell finite elements were used for FRP girder discretization. The concrete slab and the concrete cross-girders in the support regions of the superstructure were modelled using brick elements (Fig. 3). Material characteristics obtained from testing were used in the FEMs. The orthotropic properties of the laminas having different properties in different directions of fibres were also considered in modelling.

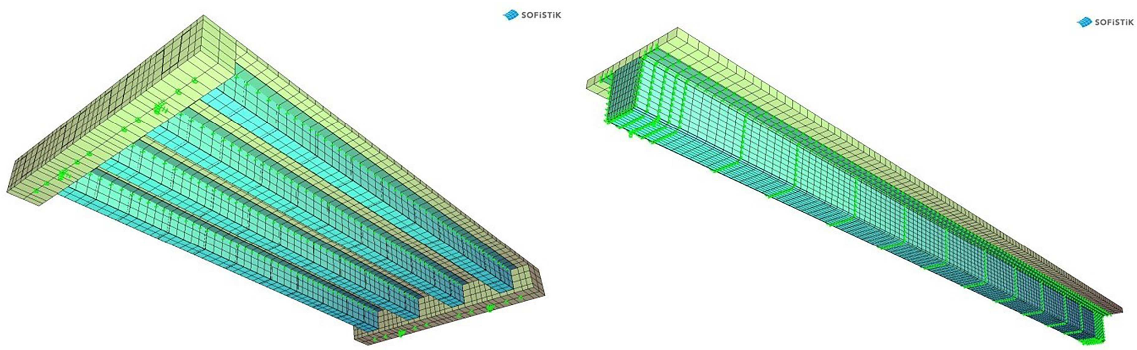

Figure 3: Numerical models of the bridge superstructure (upper) and the girder (lower)

Strength checking of laminates was performed according to three failure criteria mostly used in FRP structure design: maximum strain, Tsai - Hill and Tsai – Wu. The mean strength of each particular lamina (obtained in the material tests) was taken into account in calculation along with the material safety coefficients γ_m taken directly from the new European code proposal [5]. These coefficients take into account such effects as: creep, temperature and humidity influence on FRP material strength. The strength and stability of each girder section were numerically revealed and thus confirmed the compliance of the bridge superstructure with the service and ultimate limit states as defined in relevant codes. No failure criterion was overcome revealing the proper design and optimization of laminates which form the structure of the FRP girder.

5 The full-scale girder testing

The FEM model of the girder was validated against the test values and it was used for further structural optimization of the girder and bridge superstructure final design. The other objectives of the large-scale girder testing were to evaluate its behaviour under static load and to determine its actual carrying capacity as well as modes of failure, if any. The first step was to check the girder performance under the standard service load according to Polish code. This initial static test was followed by dynamic (modal) test of the girder to establish its main dynamic characteristics: self-frequencies and corresponding modes and logarithmic decrement of damping. Finally, the girder was loaded with quasi-static loading until failure. The ultimate carrying capacity and modes of failure was the most interested output expected at this stage of research.

Figure 4: Full-scale testing of the prototype girder

The full-scale girder with the span length of 21.0 m was statically tested in four-point bending, using two hydraulic actuators with maximum capacity of 630 kN each, mounted on a steel frame with a distance of 2.2 m (Fig. 4). During complete testing the girder behaved linearly until the applied maximum load of 1260 kN (maximum capacity of the actuators) and no residual displacement was observed after unloading. Under the maximum load, the strain of the bottom flange was equal 5.21‰, which corresponds to the tension stresses of 603 MPa in carbon laminate and 219.5 MPa in glass laminate oriented 0° in the direction of longitudinal axis of the girder. These stresses of carbon and glass laminates were only 52.6 and 25.7% of the characteristic strength of individual laminates, respectively. The concrete slab deck was not crushed under the maximum load and no cracks were observed after unloading. The girder's maximum carrying capacity determined in the test (corresponding to maximum capacity of two hydraulic actuators) was 5922 kNm (in terms of bending moment), which is at least 323% of the characteristic bending moment for which the girder was designed. Under maximum load of 1260 kN the girder had no global destruction and the total safety factor was above 3.0. However, the girder suffered several small local damages in the form of local inner and outer delamination in both flanges and at the transition zone between the web and top flange and scratch of laminate in the bottom flange (Fig. 5). In spite of local damages, based on the testing results and their comparison with design values, is was decided to apply the girder structure as tested in the bridge construction.

Figure 5: Small local damages of the girder: delamination in top flange (left) and scratch of laminate in the bottom flange (right)

6 Bridge construction

On-site bridge construction started in May 2015 with drilling of piles and casting of concrete abutment bodies. After mounting the rubber bearings, the FRP girder assembling took place, which lasted only 2 h (Fig. 6a). Subsequently, the FRP sandwich stay-in-place formwork between girders was placed and bonded to the girder's top flanges. Bonding ensured good tightness of the formwork to prevent water leakage during concrete casting. The conventional plywood formwork was used for deck slab cantilevers. After the GFRP reinforcement grids had been placed on the formwork (Fig. 6b), the slab concreting begun. Two stages of concreting were applied: initially two cross-beams at supports were cast and then the slab was poured with a lightweight concrete. This sequence of concreting ensured transverse stiffness of the superstructure and uniform dead load redistribution during casting of the slab. Finally, the deck equipment was mounted on the slab as follows: conventional deck insulation, polymer curbs and inlets, GFRP-reinforced LWC sidewalk slabs, SMA pavement along with expansion joints and finally polyurethane-based surface on sidewalks. The construction of the bridge lasted 6 months.

Figure 6: Bridge construction: (a) FRP girders assembling on-site (left); (b) deck slab reinforcement with GFRP bars (right)

7 Proof test of the bridge

The proof test of the bridge comprising static and dynamic loading was carried out by the Rzeszow University of Technology. Four 4-axis trucks with a nominal weight of 30 tons each and total weight of 128.3 tons were applied for static tests (Fig. 7a). Girder vertical displacements as well as FRP composite and concrete strains were recorded. As far as vertical displacements are concerned, the maximum measured elastic displacement in the mid-span of side girder was 30.0 mm, which is only 57.1% of theoretical value and is also less than the allowable value of 52.5 mm (L/400). The maximum elastic strain measured in the composite bottom flange was 0.521‰ and constitutes 98% of the theoretical value. It proved the efficient modelling of the FRP structure done during design stage with FEM analysis along with its appropriate material optimization. However, this real strain is far less than the limit values for carbon fibre laminas (ε_{tc} = 0.72%) as well as for glass fibre laminas (ε_{tg} = 2.61%), both used for manufacturing of girder's bottom flange.

Figure 7: Proof testing of the bridge (left) and completed bridge under service (right)

The dynamic tests were carried out with two trucks passing the bridge. The changes of girder's vertical displacement as well as accelerations in few points of the superstructure were recorded in order to evaluate the dynamic behaviour of the bridge. Basing on measured values the dynamic coefficients for various velocities (10, 30, 50 km/h) were assessed as 1.055, 1.104 and 1.163, respectively. These values are far less than the dynamic coefficient (1.25) used in bridge design according to the Polish code. The estimated first natural frequency that equalled 3.98 Hz was higher (means better) than the recommended value according to the same code (3 Hz). Moreover, the determined logarithmic decrement, used to find the damping ratio, equalled 0.087 and proved to be the appropriate damping characteristic of the bridge superstructure. The good results of all proof tests and the final inspection, which revealed no failures and damages after static and dynamic loading, were the basis for the service permission issued by the road administration (Fig. 7b).

8 Final remarks and conclusions

The Polish experience in designing, research, manufacturing and construction of the FRP composite road bridge clearly revealed that this advanced and still emerging material can be valuable alternative for conventional materials widely used in bridge construction. Since the begin of 2016 the first Polish road bridge made of FRP composites is in service and comprehensive structural health monitoring (SHM) is provided by the Rzeszow University of Technology. SHM results are believed to help further optimization of FRP composite structure and to evaluate the service life and durability of such bridges under road traffic and environment impact. Moreover, the excellent results of the demonstrative R&D project enabled the consortium to approve a new contract for the next FRP road bridge.

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