"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0

Article ID: enviro.2017.143
DOI: https://doi.org/10.3846/enviro.2017.143

Modern GFRP Composite Footbridges

Łukasz Pyrzowski[1], Mikołaj Miśkiewicz[2]

Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Gdańsk, Poland
E-mails: [1]lukasz.pyrzowski@wilis.pg.gda.pl (corresponding author); [2]mikolaj.miskiewicz@wilis.pg.gda.pl

Abstract. Application of GFRP composites in civil engineering is still not large but already noticeable. Advantages of this material, such as: low volume weight, relatively high stiffness and strength, well fatigue resistance, easiness in shaping, high material damping and high environmental resistance, make it attractive for bridge and in particular footbridge designers. It is estimated that nowadays in the world there are realized hundreds of bridges, the construction of which, whole or in part is made of GFRP. Most of them are small span structures. However, it is possible to find some interesting designs. The paper presents an overview of the most spectacular examples of footbridge structures, in which the GFRP materials plays a key role. The few examples are: Aberfeldy Footbridge in Scotland, the world's largest structure of this kind; Lleida Pedestrian Bridge, the longest arch bridge made out standard GFRP pultruded profiles or EXPO Footbridge in Lisbon, truss bridge of 30 m span length. The last example is the footbridge designed and constructed by polish consortium Fobridge. The footbridge, which arose as a result of scientific project was studied in a great details taking into account, among others: material testing, validation studies and load tests.

Keywords: modern materials, GFRP composite, footbridges.

Conference topic: Roads and railways.

Introduction

The Fibre Reinforced Polymer (FRP) is a composite material, which structure is made of minimum two components (Bank 2006). The basic ones are a reinforcement and a polymer matrix. The first one is a dispersed phase affecting the stiffness and strength of a composite. It is made of carbon, glass or aramid fibres, usually in the form of chopped stand mats or multilayer woven fabrics. The second one is a continuous phase giving a shape (monolithic nature of the product), an appropriate arrangement of reinforcement and load distribution on a volume of a composite. It is made of a polymer, which is usually an epoxy, vinylester or polyester. The characteristics of a final product called a laminate depend on the properties of materials used for each phase and on their content percentage. Composite structures are often combined in so-called sandwiches, in which the core is used as a light filler to create distance between two laminates (skins). Thus, a structure has much higher flexural stiffness. The major advantages of this material are: low volume weight, relatively high stiffness and strength, well fatigue resistance, flexibility in shaping the geometry, high material damping and high environmental and chemical resistance giving excellent long-term durability.

The development of FRP materials for commercial use started in 1930s. The first applications were processed in the defence, aviation and automotive industries. Very soon the FRP began to be used also in boats, yachts and space industry. Until today, these are the main areas of its application. As astonished examples may be given the Boeing 787 Dreamliner (see Fig. 1a), in which the composites volume content in construction material is about 80% and the Vision of The Fjords ferry (see Fig. 1b) made almost all of carbon reinforced composite materials.

Composites are being increasingly developed for a multitude of tasks. This also affected the civil engineering community (Meier 2001). Their advantages make them attractive for bridge and in particular footbridge designers (Tang, Podolny 1998). The initial phase started in 1980s, but for more than one decade materials were too expensive to compete in the construction industry. The first applications were mostly focused on strengthening and retrofitting of existing bridge structures using composite sheets and strips (Potyrała, Rius 2011). From 1990s the decrease of FRP production costs and advances in the research field, resulted in slow increase in composite application interest. Fibre reinforced composites started to replace traditional materials such as concrete, wood and metals. The composite material, which is the most popular in construction industry is the Glass Fibre Reinforced Polymer (GFRP). The reason is mainly economic.

The first bridge realizations, in which the composite materials were used, were produced using the basic wet layup process. The example may be the first FRP deck in Miyun Bridge (China) erected in 1982 (Keller 2003). Later the projects were dominated by the use of pultruded elements. The process involves a continuous pulling of the fiber rovings and mats through a resin bath and subsequently into a heated die. This technique is very popular until now. The last decade shows, that manufacturing with the use of the vacuum infusion process becomes to be more and more popular. This process uses the negative pressure of vacuum to infuse dry fibers with resin, which are placed in a mould and sealed in an airtight chamber. Vacuum infusion results in a higher price per unit weight of material than pultrusion. However, the flexibility in geometry and size is almost unlimited. It also preclude the need of joints use.

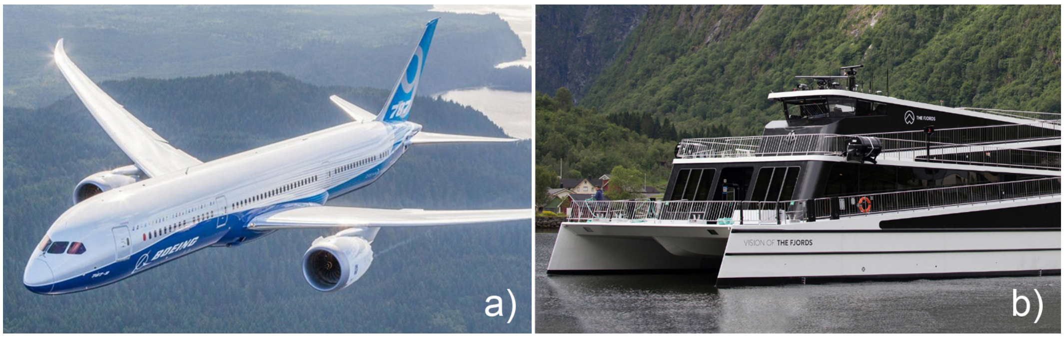

Fig. 1. a) Boeing 787 Dreamliner airplane (Source: www.boeing.com),
b) Vision of The Fjords passenger ferry (Source: www.braa.no)

The paper presents the examples of footbridge structures, in which the GFRP material plays a key role. They were chosen among many to show different static schemes and production techniques. As a main example, the project executed by the polish consortium of Gdańsk University of Technology, Military University of Technology in Warsaw and ROMA Co. Ltd. is shown. The result of this scientific research is the 14 m span length footbridge. The proposed structure has many advantages. It is durable, dynamically resistant, incombustible, easy to install and maintain and resistant to weather conditions. The project was studied in a great details taking into account, among others: material testing, validation studies and load tests.

Examples of GFRP footbridges

It is estimated that worldwide several hundred (up to thousands) bridges in whole or in a part are made of the GFRP composite materials. The presented examples creates the overview of the structural solutions, that are often the result of the used production method (hand lay-up, pultrusion, infusion). The presentation of examples starts with classic structures based on pultruded elements and finishes with sophisticated footbridges, in which the infusion production process is used.

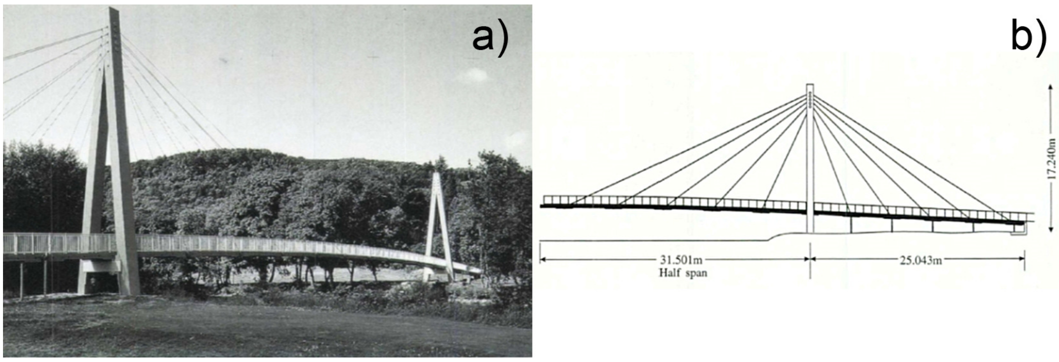

Fig. 2. Footbridge in Aberfeldy, UK: a) view, b) half of the structure elevation; (Source: Harvey 1993)

Footbridge in Aberfeldy, UK

The footbridge in Aberfeldy, UK was opened on 3rd October 1992 (Cadei, Stratford 2002; Harvey 1993). It crosses the River Tay in Scotland connecting the two halves of the golf course (see Fig. 2a). This cable-stayed structure, with A-frame towers, is still the longest span footbridge made entirely of composite materials. The total length of the structure is 113 m, made up of a 63 m main span over the river, a two back spans of 25 m (see Fig. 2b). The deck has an overall width of 2.12 m and is supported by 4 fans of 5 aramid stay cables anchored to the ground under the back spans. The bridge self-weight is 14.5 tones. The deck and towers are made of modular components pultruded from E-glass fibre and isophthalic polyester resin. Elements are connected by a combination of bonding and toggle type mechanical connectors.

Pedestrians and cyclists bridge in Kolding, Denmark

The next example of a pultruded structure is the footbridge in Kolding, Denmark (see Fig. 3a). It is the first composite bridge in Scandinavia, which was opened on 18th June 1997 (Braestrup 1999). The bridge carries pedestrians and cyclists traffic over a busy railway line. This also cable-stayed structure is 40.3 m long, including main span of 27 m. The single tower is 18.5 m height. The bridge is constructed of 12 different pultruded standard profiles and is equipped in 8 stay cables. Its total weight is 12 tones. Installation was realized within 3 nights.

Footbridge in Lleida, Spain

The following example is the footbridge in Lleida, Spain (see Fig. 3b). It was built to cross an already existing roadway, a railway line and the new projected high-speed rail-way line between Madrid and Barcelona (Sobrino, Pulido, 2002). This tied-arch footbridge has a span of 38 m, height of 6.2 m and the deck wide of 3 m. The bridge is made out of GFRP pultruded profiles. All joints are bolted using stainless steel brackets and bolts. The total weight of the bridge is approximately 19 tons. It was fabricated for only three months and erected by crane in just three hours.

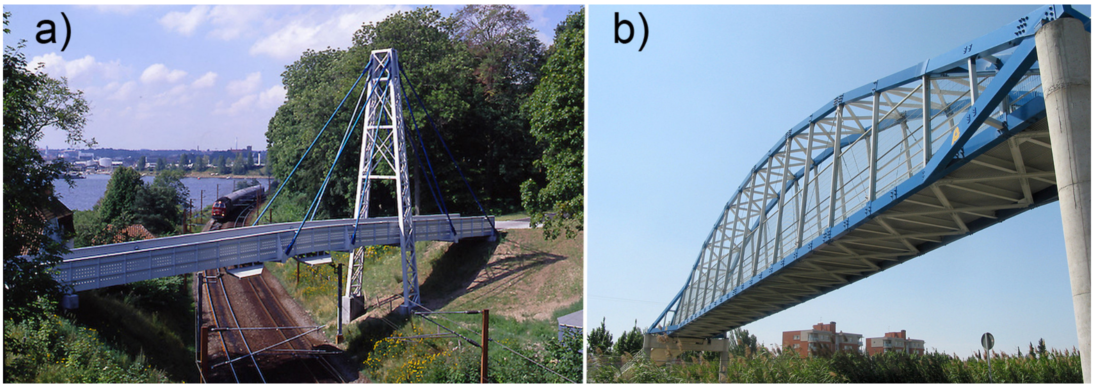

Fig. 3. a) Pedestrians and cyclists bridge in Kolding, Denmark; b) Footbridge in Lleida, Spain (Source: www.fiberline.com)

Truss footbridges

Truss bridges are the examples of typical application of pultruded profiles. Their projects are transferred directly from the idea of footbridges made of steel hot rolled or cold formed profiles (Gordziej-Zagórowska *et al.* 2016). There are many applications of this kind in the world. The examples are EXPO Bridge in Lisbon, Portugal (see Fig. 4a), which is 30 m long and weights 6.2 tons and harbour bridge in Noordland, Holland (see Fig. 4b), which has 13.5 m span length (Daniel 2003).

Fig. 4. a) EXPO Bridge in Lisbon, Portugal (Source: www.gurit.com);
b) Harbour bridge in Noordland, Holland (Source: Daniel 2003)

Footbridge in Moscow, Russia

The arch footbridge in Moscow at the park "50 years of October" is the first Russian bridge made by vacuum infusion technology (see Fig. 5a). It consist of central 22.6 m span length arch and two side beams. The width of the footbridge is 2.8 m and weight about 5 tons. The structure was installed in June 2008. All parts except metal hinges and fence fasteners are made of composite.

Bradkirk Bridge in Kirkham, UK

The Bradkirk Bridge in Kirkham, UK is a fully molded composite monocoque structure, which was manufactured using Gurit's patented Sprint out-of-autoclave epoxy (Santos, Mohan 2011). The structure comprises of two 12 m spans and two flights of steps (see Fig. 5b). Each span weighs only 1.6 tones. The bridge located over railway, replaced an existing metallic bridge that life was expired. The installation took only six hours.

Fig. 5. a) Arch footbridge in Moscow, Russia (Source: www.apatech.ru),
b) Bradkirk Bridge in Kirkham, UK (Source: own image)

Dragon's Bridge over Rhyl Harbour in North Wales, UK

The lifting bridge over Rhyl Harbour in North Wales serves as an additional crossing for pedestrians and cyclists across the River Clwyd (see Fig. 6). The footbridge was erected in 2013. Its each deck is 30 m long and weights 8 tons. The structure is mainly the sandwich type. The laminates reinforcement is a mixture of glass and carbon fabrics.

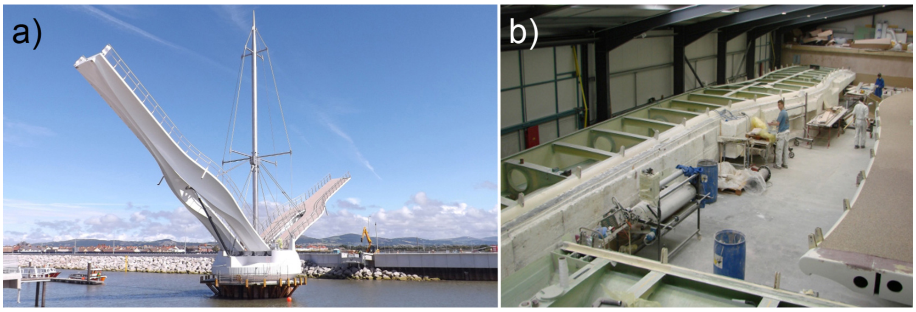

Fig. 6. Dragon's Bridge over Rhyl Harbour in North Wales, UK: a) view,
b) production of footbridge deck; (Source: www.plastics.gl)

The Ooypoort pedestrian bridge connecting Nijmegen to Ooijpolder, Denmark

The Ooypoort GFRP composite pedestrian bridge connecting Nijmegen to Ooijpolder was officially opened on 27 February 2014 (see Fig. 7). The structure of 56 m span length is among longest single-span composite bridges in the world. It was design to accommodate house boats even in case of high water levels. All composite parts of the structure were produced by vacuum infusion. Its dimensions forced production in three sections that were subsequently joined together.

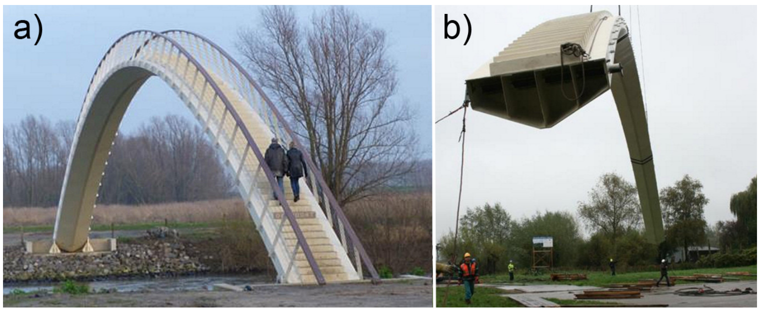

Fig. 7. The Ooypoort pedestrian bridge connecting Nijmegen to Ooijpolder, Denmark: a) view,
b) installation of footbridge; (Source: www.compositesworld.com)

Case study of FOBRIDGE footbridge in Gdańsk, Poland

In year 2015 the consortium of Gdańsk University of Technology, Military University of Technology in Warsaw and ROMA Co. Ltd. supported by NCRD (grant No. PBS/B2/6/2013) constructed the 14 m span length single element, composite footbridge, see Figure 8 (Okraszewska *et al.* 2014). The structure was constructed as a research object of the FOBRIDGE project, whose aim was to design pedestrians and cyclists bridge for use over express roads and motorways made of composite materials. The structure was designed from scratch. The project included development of concept, material selection, identification of material properties, numerical simulations, strength calculations and serviceability analyses.

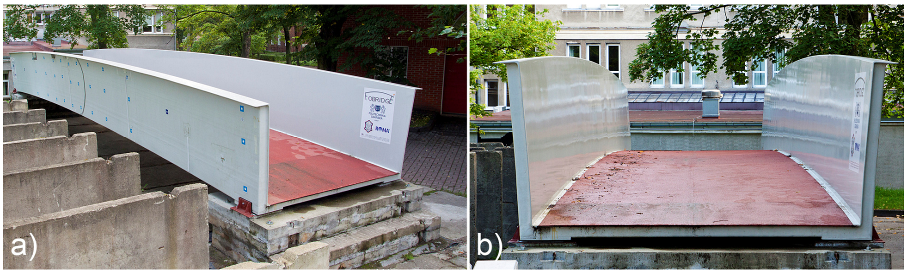

Fig. 8. Composite footbridge designed within the FOBRIDGE project in Gdańsk, Poland

The proposed structure is durable, incombustible and weather conditions resistant, which makes it easy to maintain. It is characterized by high structural stiffness and resistance to dynamic excitation. Thanks to its low weight, which is 3,4 tons, is also easy to install. The entire girder is one consistent element produced in one production cycle in standard infusion process. This allows to obtain each time high quality final product with a significant reduction of its price.

Structure description

The footbridge is a GFRP composite, U-shape, simply supported, shell-type sandwich structure. Its dimensions are: 14 m of span length, 2.6 m of deck width and 1.32 m of sides height (handrails). The footbridge is designed to carry the service load of 5 kN/m2. The structure is made of composite sandwich panels without any mechanical joints or other conventional material elements. Their outer skins are made of GFRP laminate based on vinylester flame retardant resin and a core is constructed of polyethylene terephthalate (PET) foam. The support areas are strengthened by GFRP precast elements. The manufacturing process was executed in vacuum infusion.

The FOBRIDGE footbridge was manufactured by ROMA Co. Ltd. and assembled at Gdańsk University of Technology campus, where it was subjected to a number of static and dynamic load tests.

Design work

The design work started form architectural considerations (see Fig. 9). Subsequently, it was concentrated on material selection due to mechanical properties, incombustible characteristics and economic reasons. The decision was made to use stitched and balanced BAT [0/90] and GBX [45/–45] E-glass fabrics as a reinforcement, flame retardant vinylester resin as a laminate matrix and PET foam as a core. What is worth mentioning, the use of PET foam significantly improved environment-friendliness of the footbridge. The next step was to perform material testing to identify its mechanical characteristics and to execute simultaneously numerical and validation analyses (Chróścielewski *et al.* 2017). The experimental research included tests on laminate coupons (see Fig. 10a), sandwich beams (Pyrzowski *et al.* 2016) (see Fig. 10b), up to the wide research programme for the 3 m long full-scale footbridge segment (Miśkiewicz *et al.* 2016a), see Figure 10c. After the selection of a proper numerical tools and their validation, it was possible to carry out complex calculations. Their results were the base to sizing and creating the final structural design.

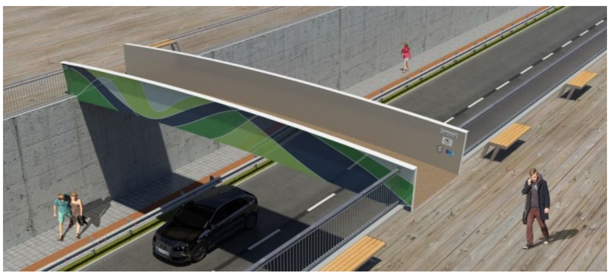

Fig. 9. Architectural concept of FOBRIDGE footbridge

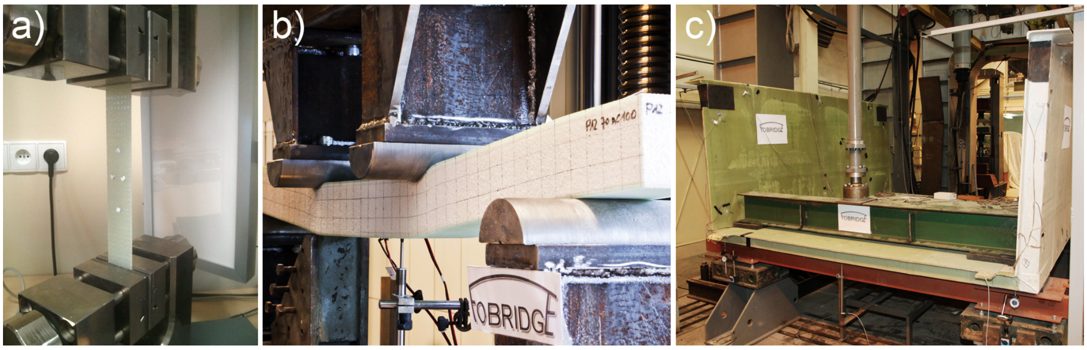

Fig. 10. Validation tests: a) coupons, b) sandwich beams, c) 3 m long segment

Manufacturing and installation of the footbridge

The footbridge was produced as one consistent element in single production cycle in standard infusion process (see Fig. 11a). The assembling of the structure at Gdańsk University of Technology campus took place on April 2015 (see Fig. 11b).

Fig. 11. a. Production of the footbridge; b. Structure assembly at Gdańsk University of Technology campus

Footbridge testing

The footbridge has been subjected to different kind of tests for one year (2015.05–2016.05). During that time, three different groups were distinguished: short-term static and dynamic load tests (see Fig. 12), long-term load test and ambient (environmental influence) testing. This complex program was created to obtain as many as possible information about the structure behaviour: statics, dynamics, creep, thermal deformation and ambient vibration. During tests many novel measurement techniques were used, e.g terrestrial laser scanning (Bernat *et al.* 2014) or fibre Bragg grating strain sensors (Li *et al.* 2014). The short-term load tests verified load carrying abilities of the analysed footbridge. The maximum applied ballast aimed to load the structure up to its designed limits, corresponding with ultimate limit state. The long-term load test verified the sensitivity of the structural material to rheological processes. All researches were finished with very satisfactory effect.

Fig. 12. Footbridge short-term testing: a) static load; b) dynamic load

In near future the footbridge will carry regular pedestrians and cyclists traffic. After completion of the research program, the structure was transported back to the manufacturer, where it is under preparation for mounting into the pedestrian and cyclist path running from Gdańsk to Pruszcz Gdański, Poland. It will span to sides of Radunia river.

Conclusions

The use of FRP composite materials in civil engineering is still not a common practice, but already noticeable. The applications are focused mainly in the bridge dFesign. The FRP composite has many excellent structural qualities that makes it attractive for designers. The most important are strength-to-weight and stiffness-to-weight ratios. Additionally, the composites may be designed for high performance, durability and extended service life. Their application can generally be economically justified taking into account that the life-cycle cost of a bridge is reduced over its lifetime. The disadvantages of FRP application are that design and manufacture require specialists from many engineering and material science disciplines, and some manufacturing processes do not produce consistent material or structural properties. It is worth to mention, that modern and sophisticated solutions should be equipped with Structural Monitoring Systems (SHM) (Mariak *et al.* 2016; Kaminski *et al.* 2015; Miśkiewicz *et al.* 2016b; Wilde *et al.* 2013). It protects against unexpected problems.

The paper presents the overview in GFRP footbridge applications. The main example shows the proposal of 14 m length footbridge created by polish consortium within Fotbridge project.

References

Bank, L. C. 2006. *Composites for construction - structural design with FRP materials*. John Wiley & Sons, Inc.

Bernat, M.; Janowski, A.; Rzepa, S.; Sobieraj, A.; Szulwic, J. 2014. Studies on the use of terrestrial laser scanning in the maintenance of buildings belonging to the cultural heritage, in *14th Geoconference on Informatics, Geoinformatics and Remote Sensing, SGEM. ORG*, Albena, Bulgaria, 307–318.

Braestrup, M. W. 1999. Footbridge constructed from glass-fibre-reinforced profiles, Denmark, *Structural Engineering International* 9(4): 256–258. https://doi.org/10.2749/101686699780481709

Cadei, J.; Stratford, T. 2002. The design, construction and in-service performance of the all-composite Aberfeldy footbridge, in *Advanced Polymer Composites for Structural Applications in Construction*, 15–17 April 2002, Southampton, UK, 445–453 [online], [cited 15 January 2017]. Available from Internet: http://www.research.ed.ac.uk/portal/files/4125311/c2002_1.pdf

Chróścielewski, J.; Miśkiewicz, M.; Pyrzowski, Ł.; Sobczyk, B.; Wilde, K. 2017. A novel sandwich footbridge - practical application of laminated composites in bridge design and in situ measurements of static response, *Composites Part B: Engineering* 126: 153–161. https://doi.org/10.1016/j.compositesb.2017.06.009

Daniel, R. A. 2003. Environmental considerations to structural material selection for a bridge, in *European Bridge Engineering Conference*, March 2003, Rotterdam, Holland [online], [cited 15 January 2017]. Available from Internet: https://www.strongwell.com/wp-content/uploads/2013/05/LCA-Pultruded-Bridge.pdf

Gordziej-Zagórowska, M.; Urbańska-Galewska, E.; Pyrzowski, Ł.; Deniziak, P.; Łukowicz, A. 2016. Preliminary experimental research on stability of truss' joint with positive eccentricity, in *13th International Conference on Metal Structures (ICMS 2016)*, 15–17 June 2016, Zielona Góra, Poland. CRC Press Taylor and Francis Group, Balkema book.

Harvey, W. J. 1993. A Reinforced Plastic Footbridge, Aberfeldy, UK. *Structural Engineering International* 3(4). https://doi.org/10.2749/101686693780607589

Kaminski, W.; Makowska, K.; Miśkiewicz, M.; Szulwic, J.; Wilde, K. 2015. System of monitoring of the Forest Opera in Sopot structure and roofing, *15th International Multidisciplinary Scientific GeoConference SGEM 2015*, *Proceedings*, 2: 471–482.

Keller, T. 2003. Use of fibre reinforced polymers in bridge construction, *IABSE Structural Engineering Documents* 7.

Li, H. N.; Yi, T. H.; Ren, L.; Li, D. S.; Huo, L. S. 2014. Reviews on innovations and applications in structural health monitoring for infrastructures, *Structural Monitoring and Maintenance* 1(1): 1–45. https://doi.org/10.12989/smm.2014.1.1.001

Mariak, A.; Miśkiewicz, M.; Meronk, B.; Pyrzowski, Ł.; Wilde, K. 2016. Reference FEM model for SHM system of cable-stayed bridge in Rzeszów, in *Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues, Proceedings of the 3rd Polish Congress of Mechanics (PCM) and 21st International Conference on Computer Methods in Mechanics (CMM)*, 8–11 September 2015, Gdansk, Poland. London: Taylor & Francis Group, 383–387.

Meier, U. 2001. Advanced solutions with composites in construction, in *International Conference on Composites in Construction 2001*, Porto, Portugal, 3–7.

Miśkiewicz, M.; Daszkiewicz, K.; Ferenc, T.; Witkowski, W.; Chróścielewski, J. 2016a. Experimental tests and numerical simulations of full scale composite sandwich segment of a foot-and cycle- bridge, in *Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues, Proceedings of the 3rd Polish Congress of Mechanics (PCM) and 21st International Conference on Computer Methods in Mechanics (CMM)*, 8–11 September 2015, Gdansk, Poland. London: Taylor & Francis Group, 401–404.

Miśkiewicz, M.; Pyrzowski, Ł.; Chróścielewski, J.; Wilde, K. 2016b. Structural health monitoring of composite shell footbridge for its design validation, in J. E. Guerrero Los Alamitos (Ed.). *Proceedings 2016 Baltic Geodetic Congress (Geomatics)*. IEEE Computer Society Order Number E5972: 228–233.

Okraszewska, R.; Pyrzowski, Ł.; Miśkiewicz, M. 2014. Composite footbridge – synergy effect in cooperation between universities and industry, in *7th International Conference of Education, Research and Innovation*, 17–19 November 2014, Seville, Spain.

Potyrała, P. B.; Rius, J. R. C. 2011. *Use of fibre reinforced polymer composites in bridge construction*. State of the Art in Hybrid and All-Composite Structures. Escola Tecnica Superior d'Enginyers de Camins, Canals i Ports de Barcelona. Universitat Politècnica de Catalunya, Departament Enginyeria de la Construcció.

Pyrzowski, Ł.; Sobczyk, B.; Witkowski, W.; Chróścielewski J. 2016. Three-point bending test of sandwich beams supporting the GFRP footbridge design process – validation, in *Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues, Proceedings of the 3rd Polish Congress of Mechanics (PCM) and 21st International Conference on Computer Methods in Mechanics (CMM)*, 8–11 September 2015, Gdansk, Poland. London: Taylor & Francis Group, 489–492.

Santos, F. M.; Mohan, M. 2011. Train buffeting measurements on a fibre-reinforced plastic composite footbridge, *Structural Engineering International* 21(3): 285–289. https://doi.org/10.2749/101686611X13049248220087

Sobrino, J. A.; Pulido, M. D. G. 2002. Towards advanced composite material footbridges, *Structural Engineering International* 12(2): 84–86. https://doi.org/10.2749/101686602777965568

Tang, B.; Podolny, W. 1998. Successful beginning for Fiber Reinforced Polymer (FRP) composite materials in bridge applications, in *International Conference on Corrosion and Rehabilitation of Reinforced Concrete Structures*, 7–11 December 1998, Orlando, USA.

Wilde, K.; Miśkiewicz, M.; Chróścielewski, J. 2013. SHM System of the roof structure of sports arena „Olivia", in *Structural Health Monitoring 2013: a roadmap to intelligent structures: proceedings of the 9th International Workshop on Structural Health Monitoring,* 10–12 September 2013, Stanford, USA. DEStech Publications, 2: 1745–1752.