RESEARCH ARTICLE

The Resistance to UV Radiation for GFRP Pultruded Bridge Panels

*Beata Stankiewicz**

Depending on the type of the load which affects the durability and design life glass fibre reinforced polymer (GFRP) structures should be designed so as to take into account as first of all the chemical-physical conditions in which the structure is used including: ultraviolet (UV) radiation, temperature influences, humidity, water and chemicals. The results presented herein provide a predictions regarding of the mechanisms involved in the ageing of GFRP pultruded bridge profiles and predicting the property micro scale changes with time and remaining service life of GFRP under real environmental degradation impacts and during simulation laboratory conditions. The outermost layers of FRP (fibre reinforced polymer) composites are damaged mostly because of UV radiation. Radiation also induces remarkable microstructural changes depending on wavelength and intensity, and oxygen availability, eventually leading to polymer chain scission. A scanning electron microscope (SEM) was used to investigate the degradation mechanism of the GFRP samples subjected among others to UV radiation and water vapor condensation. Glass fibre-reinforced polymer GFRP pultruded profiles have great potential in the construction industry, presenting several advantages comparing with traditional materials, among which, the potentially improved durability under environmental influents.

Introduction

In the twenty-first century, advanced FRP composite materials will witness steady and widespread growth in the civil infrastructure arena. The recent launch of new design codes and the development of new products for civil construction will create new opportunities for the composite industry. The outermost layers of FRP (fiber reinforced polymer) composites are damaged mostly because of UV radiation. As regards moisture, penetration depends on several factors, such as time of exposure and profile geometry. Knowledge is markedly lacking in these aspects of the performance of FRP commercial profiles currently used for different constructional applications [**1**]. Depending on the type of the load which affects the durability and design life (according to EN 1990), FRP structures should be designed so as to take into account as first of all the chemical-physical conditions in which the structure is used including: ultraviolet (UV) radiation, temperature influences, humidity, water and chemicals. There are two important subjects fatigue and the accidental loads (according to EN 1991-1-7). The cycle of FRP construction life divides into the transportation phase, the installation phase and the inspection and maintenance phases [**2**]. Glass fibers exhibit good resistance to UV radiation. The polymeric matrix of FRP materials is susceptible to photo degradation initiated by the UV component of solar radiation. However, the most deleterious effects of UV radiation on FRP materials are not due to direct photolytic effects, which are limited to the surface regions, but to the increased propensity for moisture and aqueous solutions to ingress into the material structure. Superficial crazing and cracking can potentially serve as sites for moisture sorption and fracture initiation. After prolonged periods of exposure, as damage progresses into the bulk, fiber matrix inter phase could be reached, and both physical and mechanical properties could exhibit significant changes [**3**]. For durability investigation of natural FRP composites, Libo Yan *et. al.* investigated, the combined effect of UV radiation and water spraying on the mechanical properties of epoxy composites used for civil engineering application. UV radiation and water spraying caused severe discoloration matrix erosion, microcracking and void formation of the composites [**4**]. Dionysis *et. al.* studied the combined action of temperature, humidity and UV radiation on polymers and composites. The results showed that after exposure the polymer matrix became stiffer in an irreversible way. Some studies also simulated harsh environments with immersion in water solutions, such as alkali, acid, or salt to investigate the long-term

Faculty of Civil Engineering and Architecture, Opole University of Technology, Katowicka Str. 48, 45-061 Opole, Poland

*Corresponding author:
E-mail: b.stankiewicz@po.edu.pl

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performance of FRP composites [5-8]. Corrosive environment, exposed to solar radiation and seawater, can significantly reduce their structural integrity, especially when associated to cyclic stresses. Water absorption and exposure to salinity cause considerable microstructural changes in FRP composites, invariably decreasing their mechanical strength due to fiber-matrix interface degradation. These changes become irreversible due to chemical interaction between water molecules and resin functional groups for long-term ageing. Radiation also induces remarkable microstructural changes depending on wavelength and intensity, and oxygen availability, eventually leading to polymer chain scission [9]. Glass Fiber Reinforced Polymer (GFRP) has been commonly used as outer layer, and it may expose to the ultraviolet exposure and prone to UV radiation. UV radiation will lead to degradation of the GFRP itself and it will reduce the quality and function of GFRP. Mechanical degradation and damaging in structural integrity can happen under some circumstances, causing from surrounding environments [10]. Aging during normal service conditions: this is the most difficult case to treat because of the very low rate of the degradation processes in real life for GFRP. In order to establish aging model and to predict lifetime in real usage conditions, one needs to rely on accelerated aging test. A compromise between being a representative of the reality and the duration of the test is carefully addressed when using accelerated aging test. Most of the studies are based on accelerated aging test and required extrapolation to normal service conditions. Many factors, such as temperature, irradiation, moisture, chemicals, and presence of an active physical stress, can significantly affect the durability of the polymeric material [11-12]. The combined action of both UV and water on polymers as a function of time and temperature could be even more severe than the individual effects. Most importantly the sums of the individual UV and water condensation aging effects on weight changes are positive with weight gains, whereas the weight changes under the cyclic combined conditions are negative with weight losses for all tested composites [13]. When a polymer is subjected to ultraviolet radiation it releases constituents in the form of thin, loosely adherent dust. This coating defect called chalking. Coatings are expected to be durable and retain their properties over time. As such, resistance to light, humidity and temperature is a general requirement. The environmental impact of coatings can be further reduced by increasing their efficiency and useful life. The most common cause of coating degradation is ambient exposure to ultraviolet (UV) radiation, water/humidity and temperature fluctuation. In many cases, degradation is evaluated based on changes in chemical structure and the presence of foreign chemicals in the system as a function of time [14]. The thermal cycling degradation process of a pultruded GFRP profile is investigated by Sotirios *et. al.* [15]. Some investigated results indicate that no significant correlation was observed between the sustained stress level and the rate of degradation of the mechanical properties of the composites. It was investigated by Mohammad *et. al.* [16] this indicates that no synergistic effect on the degradation rate of pultruded GFRP exists between mechanical and environmental loading at stress levels encountered during the service life of FRP structures. The first part of author' investigation was included comprehensive analysis of GFRP pultruded composite, acquired from cable-stayed Fiberline Bridge exploited for 20 years in the fjord area of Kolding, Denmark. During previous research, fragment of composite material used for Fourier transform infrared (FT-IR), TGA, DSC, and DMA tests was therefore subjected to natural aging as a result of temperature amplitudes, permanent solar radiation as well as aggressive impact of sea salt contained in the moisture in the air around coastal area. Complex comparative analyses presented in previous investigation, and based on FT-IR, TGA, DSC, and DMA tests, pertained to both unspool, virgin composite GFRP material (composite 1) and the one after 20 years of natural aging (composite 2). The presented new research holds analysis of UV radiation for twenty years old GFRP composite in laboratory condition under xenon lamp, based on regulations from ISO 4892-2 normative [17]. The research thesis was about a scale of influence of UV and other climatic implications like water in order to observe particular changes in all-GFRP structure. For how it will be possible to exploit without essential changes in the material of construction bridge elements, in continue service life after the first twenty years period.

Experimental program

Materials

Advanced composites such as glass fiber-reinforced polymers (GFRP) integrate features essential for future materials such as formability, low weight, high tensile and compressive strength and cost-effectiveness, thus one suitable for tailored components in many different industries. Composites typically consist of a matrix component (e.g., resin matrix) and a reinforcement component (e.g., glass fibers) to achieve specific mechanical properties. Glass Fiber Reinforced Polymer, sample material used to construct 12 bridge profiles of Kolding Footbridge (**Fig. 1**) was made of alternating layers of unidirectional E-glass fibers roving and strand mats embedded in polymer resin matrix. The matrix of glass fibers is a mixed consistency on epoxy resin with amine bisphenol A and epoxy polyester aliphatic by isophthalic polyester. The fiber fractions are approximately 50% per volume or 70% per weight. The matrix is a protecting cover for fiber and it is responsible for load propagation. The GFRP pultruded material used in the experimental campaign was supplied by Fiberline and consists of virgin material and aging composite required from existing all-composite structure of Kolding Footbridge in Denmark. European Standard EN 13706 applies solely to pultruded Fiberline profiles for "structural purposes", which according to the standard are defined as "where the load-bearing characteristic is the major criterion of design and where the product is part of a load-bearing system" (**Table 1**).

Table 1. Properties of GFRP Fiberline virgin composite of bridge panels in Kolding Footbridge in 1997.

Characteristic properties			Minimum requirements	
Properties	**Unit**	**Test method**	**E23**	**E17**
Modulus of eleasticity	GPa	Annex D, EN 13706-2:2002	23	17
Tensile modulus - longitudinal	GPa	EN ISO 527-4	23	17
Tensile modulus - transverse	GPa	EN ISO 527-4	7	5
Tensile strength - longitudinal	MPa	EN ISO 527-4	240	170
Tensile strength - transverse*	MPa	EN ISO 527-4	50	30
Pin-bearing strength - longitudinal	MPa	Annex E, EN 13706-2:2002	150	90
Pin-bearing strength - transverse	MPa	Annex E, EN 13706-2:2002	70	50
Bending strength - longitudinal	MPa	EN ISO 14125	240	170
Bending strength - transverse	MPa	EN ISO 14125	100	70
Shear strength - longitudinal	MPa	EN ISO 14130	25	15

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Fig. 1. All-GFRP Kolding Fiberline Footbridge, Denmark.

GFRP Fiberline construction bridge profiles and HD/MD planks have a 400 μm polyester surface mat that keeps the main structural fibers (in this case the mats) away from the surface. Due to external environmental influences, such as UV light or abrasive wear, the first layer of the GFRP profiles will wear out and change color over time. The main carrying fibers are not attacked thereby and thus the mechanical properties remain the same. However, the surface becomes rough and dirty, which can affect the aesthetic appearance. Therefore, the recommendation is to use a color coating of 60 μm. This coating system should not affect the durability, but rather ensure the attractiveness of the structure over decades. The perfect example of all-GFRP composite structure with protection of blue color coating of 60 μm is arch all-GFRP Lleida Footbridge in Spain, in Catalonia (**Fig. 2**).

Fig. 2. All-GFRP arch Lleida Footbridge in Spain.

Methods

Dynamic Material Analysis (DMA) of GFRP material after 20 years of service life

There are several prevalent methods to evaluate the aging of polymer materials. The most direct method is empirical appearance discrimination, which is routinely used albeit being the least accurate. More systematic approaches such as thermal analytical methods, including thermo gravimetric analysis, differential thermal analysis and differential scanning calorimetry are based on the material's thermal effect during its aging. During author' previous investigation, in order to determine the influence of air temperature on the storage and loss modulus of GFRP material acquired from the Fiberline Bridge the dynamic mechanical analysis (DMA) was performed for both (1) the intact GFRP pultruded material, namely virgin material, denoted as Sample No. 1 (the test was done in 1997); and (2) the actual GFRP material acquired after 20 years of natural aging, denoted as Sample No. 2 (the test was done in 2017). The DMA analysis is one of the most useful tools for studying the viscoelastic thermal behavior of polymers and composites. Within the frame of DMA, samples are subjected to a sinusoidal mechanical oscillation at a fixed frequency, while the temperature increases at a constant rate. Under such conditions the amplitudes of the load, deformation cycles as well as the phase angles between these cycles are measured. Finally, DMA provides quantitative determination of mechanical properties of a sample under oscillating load as a function of temperature, time and frequency. In this study, DMA was carried out on an DMA/SDTA861e apparatus from Mettler Toledo. An oscillatory dual cantilever bending deformation with displacement amplitude of 10 μm, force amplitude of 2N at the constant frequency of 5 Hz and at the heating rate of 2 K/min (the possible temperature range was from -40°C to + 200°C) were applied. The values of storage modulus E', loss modulus E'' and loss factor tan δ = E''/E' were recorded as functions of temperature. Samples No. 1 (1997) and No. 2 (2017) as rectangular beams measuring 90×10×3.5 mm were inserted into clamps for sample fixation. Sample material was made of alternating layers of unidirectional E-glass fiber roving and strand mats embedded in polymer resin matrix. The influence of the temperature on the storage modulus of GFRP material, representing the elastic material behavior, was tested by DMA. The previous test was performed for both the intact material used in the Fiberline Bridge construction in 1997 and material acquired from the Fiberline Bridge after 20 years of natural aging. **Fig. 3** presents changes in E' and tan δ as functions of temperature determined for Samples No. 1 and No. 2 within the range of the natural environmental temperature from - 20°C to + 30°C. DMA has shown that both materials have similar thermomechanical properties what suggests an excellent thermal stability of composite material after 20 years of service life. It was found that the storage modulus of this material varies with almost linear relation from 9168 MPa to 8908 MPa within the range of the natural environmental temperature occurring in the bridge location conditions, i.e., from -20°C to 30°C. For example, the change of the temperature for 10°C causes the change of the storage modulus for about 0.5%.

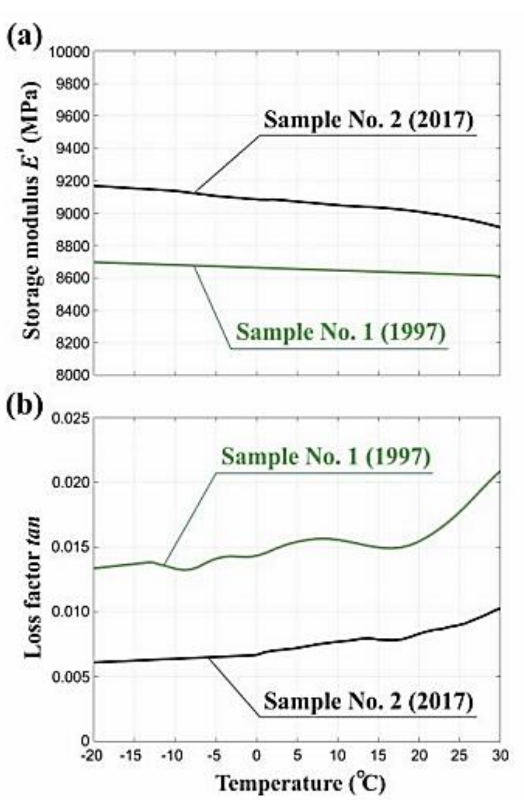


Fig. 3. DMA thermograms of Samples No. 1 (1997) and No. 2 (2017): (a) storage modulus *E'*; and (b) loss actor *tan δ* as a function of temperature within real environmental temperature range.

Fig. 4. Ci4000 Atlas Weather-Ometer®, equipped with a xenon lamp.

Exposure environments in presented new research cycle Experimental procedures

The described research consists of analysis of UV radiation for the twenty years old GFRP composite samples, in laboratory condition under xenon lamp, based on regulations from ISO 4892-2 normative [**17**]. The pultruded GFRP laminates investigated in this study consisted of E-glass fibers with density of 2,53 g/cm^3 embedded in isophtalic polyester resin, in investigation samples 120×16×4 mm. The glass fibers content was determined by the calcinations method described in ASTM D 3171 [**18**], and the density was determined by the immersion method described in ISO 1183 [**19**]. The new Ci4000 Weather-Ometer® performed accelerated material durability testing according to a wide range of standards (ASTM, ISO, SAE, etc.). The intensity of the UV radiation was 388,8 MJ/m^2, using Ci4000 Atlas Weather-Ometer® (**Fig. 4**) apparatus (aging chamber) with the presence of water enhancing the damage effect of UV radiation. Finally, these samples were exposed to UV to conduct microphotography and to observe the delamination and fracture of the matrix by making sectional cuts. Through the Xenotest it is possible submit components and accelerated specimens exposure to light recreating the same effects of aging from solar radiation products, with the temperature and humidity control. The xenon arc lamp reproduces more faithfully the solar radiation spectrum, ensuring greater reliability then compared with the simpler aging UV. GFRP aged (20 years old bridge element) composites were subjected to exposure under xenon UV lamp. Such studies simulate an ageing process in natural conditions of degradation. The samples with 120×16×4 mm dimension underwent exposure in

Ci4000 Weather-Ometer®, equipped with xenon lamp as the radiation source. The examination was carried out for 1893,3 h samples were subjected to irradiation of 388,8 MJ/m^2 (within scope of 300-400 nm) equivalent to a 1,5-year permanent UV exposure in the natural environment. SEM pictures from the cross section of examined samples, dusted with graphite, where achieved using an electronic comprehensive scanning microscope, during the first phase of research. Scanning Electron Microscopy was created by JEOL equipment with Energy Dispersive Spectroscopy decoder (EDS system). **Fig. 4** includes SEM images of the cross-sections of GFRP sample before laboratory UV exposure, but after synergistic effects of environmental impact in real outdoor condition, during 20 years of exploitation of bridge GFRP panel.

Testing the resistance of the supplied samples to the effects of weather conditions causing the so-called atmospheric aging was carried out in accordance with the PN-EN ISO 4898-2 standard in the aging chamber of the Ci4000 Weather-Ometer®, equipped with a xenon lamp being the source of radiation. Test method A1 with daylight filters was used. The test conditions are given in the **Table 2**.

Table 2. The conditions of aging test in apparatus Ci4000 Weather-Ometer® according to ISO 4892-2.

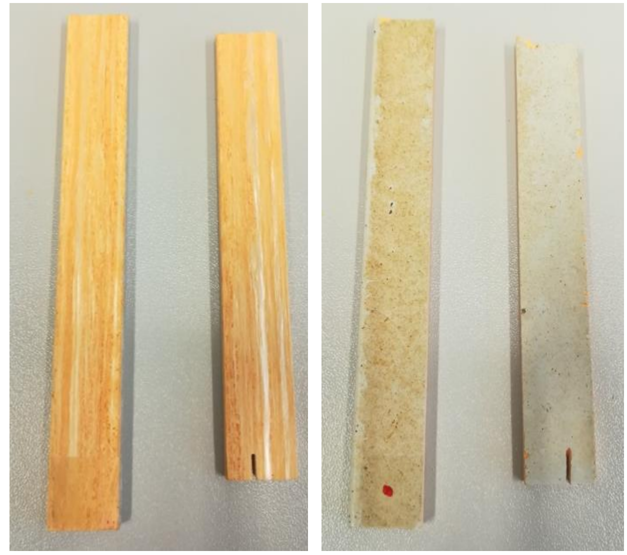
Parameter		Phase I	Phase II
Filter set		300-400 nm	
Radiation intensity	Wide band (300-400 nm)	60 ± 2 W/m^2	
	Narrow band (340 nm)	0,51 ± 0,02 W/m^2	
Carousel mode		With a turn	
Temperature control		Chamber and black pattern thermometer (BST)	
Phase length		102 min.	18 min.
Chamber temperature		38,0 ± 3 °C	- *
Black pattern temperature (BST)		65,0 ± 3 °C	- *
Relative humidity		50 ± 10 %	Rain
Rain simulation		No	Yes
Time of test		1893,3 h	

* Parameters resulting from the conditions in the apparatus.

Under the test conditions as shown in the **Table 2**, the UV radiation dose absorbed by the samples, measured in the range of 300-400 nm, was 408.96 MJ/m^2. This is equivalent to just over 1.5 years of natural aging under the influence of sunlight in our latitude.

Analysis of morphological properties by SEM method, two aged composite samples

The objects of the research were two composite bars aged in Xenotest and presented in **Fig. 5**. Outside surface of two GFRP samples (ND) and (CD) and interior plane (NG) and (CG). The samples were after 21,5 years old of sun radiation, during the first period in natural environmental impact (20 years) and then during the second period in laboratory, based on Xenotest (simulated 1,5 year).



GFRP(NG) GFRP(CG) GFRP(ND) GFRP(CD)

Fig. 5. Aging GFRP 21,5 years old elements, using in morphology SEM test.

The subject of the research were also composite GFRP elements not aged in Xenotest and not aged in natural environment as a reference virgin material: GFRP(NN), GFRP(NNN), GFRP(NCW). Parameters of test morphology and kind of microscope observation: the name of the machine Hitachi TM3000 camera, type of EDS pickup, electron beam voltage 15 keV, sputtering Au/Pd, spraying time 180 s. Image analysis of the surface structure of films using the SEM method: 50x, 200x, 800x, 2000x, 4000x (**Fig. 6**) was prepared.

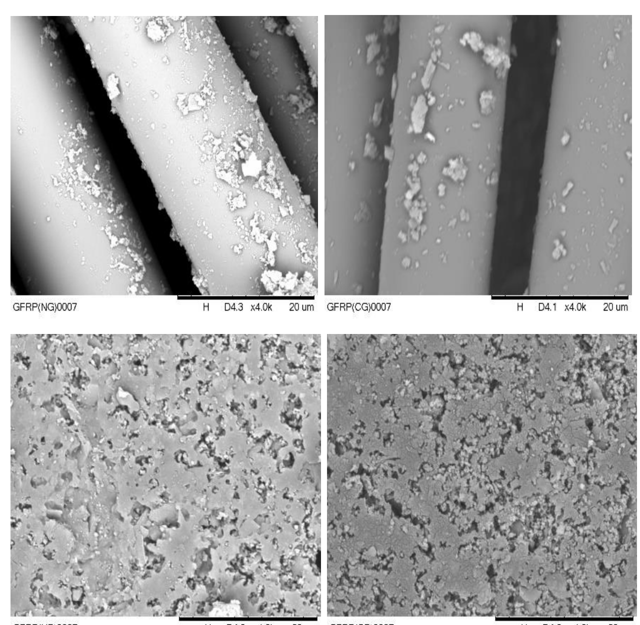


Fig. 6. SEM image of films no GFRP(CG), GFRP(CD), GFRP(NG), GFRP(ND) with magnification 4000x.

Results and discussion

The ultraviolet radiation during 1893,3 h, however, did not result any severe degradation. The methodology requires that various impact series should be performed at different energies and that the evolution of the damage is followed by immersion SEM inspection to quantify how the material behaves, in addition to evaluating the delamination process via penetrating dyes using UV radiation. The polymer, which absorbs the ultraviolet radiation, modifies its chemical structure, providing molecular chain scission and/or cross linking. All scales of polymer dimension, including the monomer unit, the chain (cross linking or chain scission), and the morphology (breakdown of tie molecules and crystal) change due to photo-degradation. Due to the degradation of fibers and matrix after weathering periods, the polymer composite loses its tensile strength. Therefore, it is necessary to highlight some of the research evolution of UV radiation effects towards composite material and open further areas of study related to UV degradation towards properties of polymer matrix composites [**20**]. The results of Bazli M. *et. al.* research showed that the mechanical properties of various GFRP sections generally decreased with the duration of conditioning: however, the rate of the decrease that was only slight up to 1000 h, increased rapidly during 1000-2000 h, and again it was slow during 2000-3000 h. The maximum reductions were 34%, 28% and 23% after exposure to 3000 h cycles for bending, tensile and compression tests, respectively [**1**]. The results of Tuwair H. *et. al.* study revealed that GFRP bridge panels' degradation did exist due to the effects of thermal cycling and the de-icing solution. The ultraviolet radiation, however, did not cause any degradation [**21**]**.** FRP bridge deck panels are exposed to multiple environmental conditions (i.e., moisture, alkali environment, thermal, creep/relaxation, fatigue, ultraviolet exposure, and fire) during their service lifetime, which causes the synergistic degradation mechanism [**22**].

However, durability of GFRP composites used in bridge applications depends on kind of polymer resin, kind of glass fibers and outdoor protected surface which covers panels. As expected, no significant macro cracks macro structural or damages appeared within the resin matrix after exposure to environmental conditions. The longer the conditioning period, the greater the number of micro-cracks and damages were observed based on SEM comparative analysis (**Fig. 6**). There were also instances of fiber/resin deboning at the surface after the period specified exposure which confirms the detrained effect of UV radiation and water. Furthermore, the exposure to the UV radiations has a losses impact than the continuous condensation treatment: first of all, it is due to the presence of the UV absorbance film, and, furthermore, it is well known that high humidity levels can seriously affect mechanical performances of the adhesives. The capacity of UV radiation in 1893,3 h (during research laboratory days) means one and half year of standard UV radiation under real environmental condition, in European climate zoon.

Conclusion

The test results and comparative analysis of environmental reduction factors are presented and discussed in this paper. UV radiation and water vapour condensation conditions did not show a significant effect in macro scale. A scanning electron microscope (SEM) was used to investigate the degradation mechanism of the GFRP samples subjected to UV radiation and water vapour condensation. Visually no damage was noticed in 20 years old GFRP samples when exposed to UV + water spray aging after radiation cycles. UV radiation has been linked to the degradation of GFRP composite materials with the degradation rate depending on some key parameters such as UV wavelength, exposure time and UV intensity. Effects of sequential exposure to UV radiation and water vapour condensation were certificated during lab test using Ci4000 Atlas Weather-Ometer® apparatus. The high resistance to UV radiation of GFRP Fiberline bridge panels has been achieved based on specialist procedure in accordance with normative regulations. The outer surface of GFRP composite shows no signs of aging by intense simulated UV. The morphological SEM investigation shows the microscopic loss of adhesion of the fibers to the matrix which will progress, although micro structural changes are not rapid and drastic by matrix erosion, during 21,5 years of GFRP elements entire life. The previous DMA analysis was favorable for the aged GFRP elements, but complementary strength analyzes of GFRP members subjected to fatigue loads in the bridge structure would be essential.

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Conflicts of interest

There are no conflicts to declare.

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Author biography

I have finished Gdansk University of Technology in Poland in 1987, as master of bridge structures. I started work at Opole University of Technology (Poland) in 2000 as PhD, at Civil Engineering Faculty in Roads and Bridges Department. The focus of basic research interest is GFRP composite materials application in bridge structures, durability of GFRP and comparison analysis with traditional materials in bridge structures elements. The own Faculty lectures are Concrete Bridges, Composite Materials in Bridges, Transport Bridge and Roads Infrastructure. The results of personal research were published in Journal of Composite Materials by Sage Press, in Steel and Composite Structures by Techno Press, in Measurement by Elsevier and Materials by MDPI.