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COMPOSITES THEORY AND PRACTICE

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DAMAGE IMPACT ON LOAD-CARRYING STRENGTH OF FIBER REINFORCED POLYMERS COMPOSITES TO BE USED IN BRIDGE ENGINEERING

Fiber reinforced polymer composites (FRP composites) are advanced technical materials nowadays, offering broad applications in bridge engineering science. This work is aimed at analysing FRP composite damage in static tensile tests, by assessing the load-carrying capacities of the tested specimens. For the tests, demonstrative scale composites for constructing structural components of the load-carrying girder of a bridge structure were used. Such materials are considered an alternative for steel and concrete today as they have superior strength parameters. This is shown by their higher maximum load values. In this work, several typical types of FRP composites damage in tensile tests are analysed. The damage in the form of local warp degradation (warp crushing) caused by mechanical impact reduced the load-carrying capacity of the specimens by 45%. The manufacturing defects, consisting in textile creasing while placing in the mould, and the introduction of holes for mechanical fixation of structural components also reduce the load-carrying capacity to about 20%.

Keywords: reinforced fiber polymers, composite load-carrying capacity, damage

WPŁYW USZKODZEŃ NA NOŚNOŚĆ KOMPOZYTÓW WŁÓKNISTYCH O OSNOWIE POLIMEROWEJ DO ZASTOSOWAŃ W INŻYNIERII MOSTOWEJ

Kompozyty polimerowe wzmocnione włóknem (kompozyty FRP) są obecnie zaawansowanymi materiałami technicznymi, mającymi szerokie zastosowanie w inżynierii mostowej. Prezentowana praca ma na celu analizę zniszczenia kompozytów FRP, poddanych statycznej próbie rozciągania poprzez ocenę charakterystyk nośności badanych próbek. W badaniach wykorzystano kompozyty w skali demonstracyjnej do budowy elementów konstrukcyjnych dźwigara nośnego obiektu mostowego. Takie materiały uważane są dziś za zamiennik dla stali i betonu, ponieważ odznaczają się wyższymi parametrami wytrzymałościowymi. Świadczą o tym wyższe poziomy maksymalnego obciążenia. W pracy przeanalizowano kilka typowych uszkodzeń kompozytów FRP poddanych naprężeniom rozciągającym. Wprowadzenie uszkodzenia w postaci lokalnej degradacji osnowy (miażdżenie osnowy) wywołane mechanicznym uderzeniem wpłynęło na obniżenie nośności próbek do 45%. Na obniżenie nośności do około 20% wpływają również wady produkcyjne polegające na pofałdowaniu tkanin podczas rozkładania w formie oraz wprowadzenie otworów stosowanych do połączeń mechanicznych elementów konstrukcji.

Słowa kluczowe: kompozyty włókniste o osnowie polimerowej, nośność laminatów, zniszczenie

INTRODUCTION

The macroscopic properties of a polymer depend on the physical properties of the warp and reinforcement (fibers, particles) and on the relative content of the warp (V_w) and reinforcement (V_r) taken volumetrically ($V_w + V_r = 100\%$). The warp's role consists in protecting the reinforcement, transferring external loads and ensuring the required shape of the structural component. The reinforcement ensures high mechanical properties of the polymer and reinforces the warp in selected directions [1]. Polymers reinforced with long and orderly fibers are anisothropic materials. The fibers can be unidirectional or woven into a textile. The unidirectional arrangement of the fibers ensures higher mechanical properties and lower creeping disposition when compared with short fibers [2].

The most popular reinforcement types used in polymer-warp composites include glass fibers - G and carbon fibers - C or their combination GC. This is why polymers reinforced with glass fibers are marked by the abbreviation GRFP while those reinforced with carbon fibers - CFRP and with glass and carbon ones - GCFRP. The wide application of GFRP composites in industry stems from their mechanical properties and relatively low price. GFRP offer higher specific strength. CGFRP composites enable one to balance the economic aspects and mechanical properties. The application of the above-mentioned composites offers numerous advantages from the perspective of strength and stiffness with a low specific weight, resistance to corrosion as well as aesthetic and utilitarian properties. However, the combination of glass and carbon fibers generates many undesirable damage mechanisms, such as fiber shearing or delamination.

Polymer warps are most frequent in FRP composites as they are cheap and offer physico-chemical properties sufficient for most composite working conditions. Polymer warps can be divided into thermoset or thermoplastic. The most important of thermoset polymers is epoxy resins ensuring products with exact geometrical shapes. A laminated composite is a structure composed of single layers. As for every other engineering structure, it has its specific load-carrying capacity. "Strength" is used to describe a single composite layer, being a laminate component [3]. This is why the laminate load-carrying capacity is theoretically determined by checking the strength of every single layer and by indicating the one that gets damaged as the first one. In practice, the theoretical model using the Classical Lamination Theory is employed here [4]. Numerous failure criteria, such as maximum stress, Tsai-Wu, Tsai-Hill, indicating the combined stress when the damage takes place, are used here [5].

Using FRP composites for bridge erection is a relatively new technology when compared to conventional ones. Bridge structures degrade in the course of their operation and for this reason an objective methodology to assess their technical condition and fitness for use must be developed. In Poland, the strategy of systematic monitoring of the bridge infrastructure condition through inspections is implemented. Its main objective is detection and identification of defects. The degradation processes of bridges are used as a criterion for classification of damage. In the literature [6, 7] hierarchical classification methods for defects in basic bridge construction materials are proposed.

For some bridge structures made from FRP composites, there are no operation data as they have been operating for a short time. There are no experts' systems either for the technical condition assessment of such bridges. In the future, the examinations presented in this article can be used in research systems for classifying and monitoring defects in present composite engineering structures.

MATERIALS AND METHODOLOGY

The multi-layered structure of the studied GCFRP composite was produced in the infusion process and is composed of six glass and fifteen carbon layers (Fig. 1c). The warp of these composites is made of epoxy resin. The relative reinforcement content is V_r = 55% and its properties are presented in Table 1.

At the first stage of the studies, a GCFRP laminate sheet was made, sized 1800 x 18000 mm. The layer arrangement in the prepared laminate reflects the structure of the lower section of the load-carrying girder of the bridge structure, transferring tensile load (Fig. 1). Depending on the measurement location, the laminate sample thickness belonged to the range from 14 to 15 mm. 1600 mm samples with a section of 14-15 x 80 mm were cut from the prepared sheet.

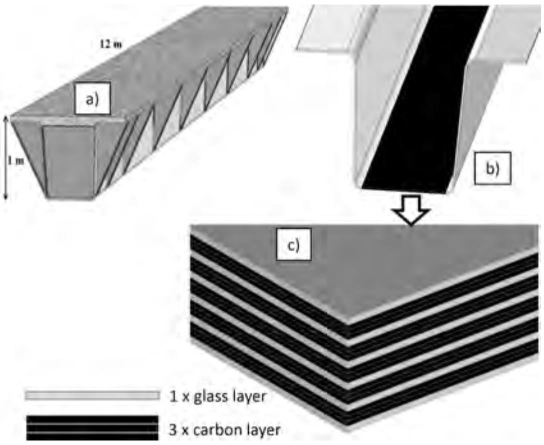

Fig. 1. Diagram of bridge girder: a) outline, b) location of GCFRP composite, c) layer arrangement in GCFRP composite

Rys. 1. Schemat budowy dźwigara obiektu mostowego: a) koncepcja ogólna, b) lokalizacja kompozytu GCFRP, c) układ warstw w kompozycie GCFRP

TABLE 1. **Characteristics of selected glass and carbon fiber reinforcement**

TABELA 1. **Charakterystyka wybranego zbrojenia z włókna szklanego i węglowego**

Material	Type	Fiber direction	Grammature [g/m^2]
Glass fiber	Bi-directional fabric	[-45°, +45°]	600
Carbon fiber	Unidirectional fabric	[0°]	1200

Artificial defects were introduced into the cut samples, in the form of delamination, local warp degradation (warp crushing) and holes.

Other samples were cut from the laminate derived directly from the demonstrative bridge girder where manufacturing defects in the form of textile folds were detected in the laminate, as shown in Figure 2.

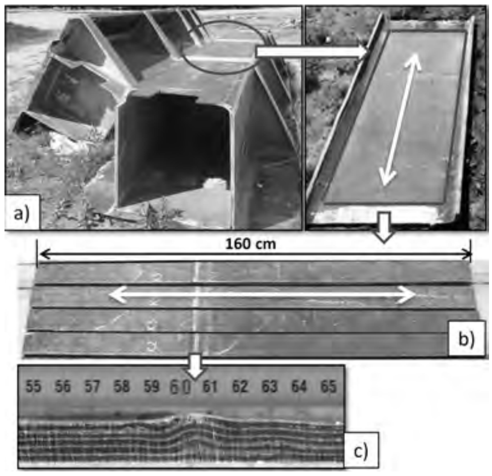

Fig. 2. Damaged demonstrative girder made from GCFRP composite: a) location where material for studies was derived from, b) sample cutting method; cross-section with folds

Rys. 2. Zniszczony demonstracyjny dźwigar z kompozytu GCFRP: a) miejsce pozyskania materiału do badań, b) sposób wycięcia próbek, c) przekrój poprzeczny z widocznym pofałdowaniem

The static tensile tests were carried out on an Instron J1D universal testing machine, with forces ranging ±1200 kN. The samples were subject to uniaxial expansion with the load growing gradually. The constant load speed was pre-set and controlled automatically until the sample was damaged. The beam of the universal testing machine travelled 0.2 mm/min.

TEST RESULTS

In this work, the analytical limit curves of the load-carrying capacity of the target GCFRP composite were determined analytically, based on the proprietary experimental strength characteristics of the glass and carbon layers (Fig. 3). The load-carrying capacity of the composite was defined as the mean value of stress in the layers in the function of laminate thickness. The stress in the layers and the load-carrying capacity of the composite were analysed in the area of major stress (σ_x, σ_y) according to the failure criteria of maximum stress, Tsai-Wu and Tsai-Hill. The "x" and "y" directions indicate the longitudinal and lateral direction of the sample respectively. The theoretical analysis was verified against the results obtained in the static tensile test for the reference samples (GCFRP composite with target thickness).

The diagram presented in Figure 3 shows that all the analysed failure criteria offer similar load-carrying capacity values for the tested composite. Additionally, the prognosed theoretical model is similar to the experimental results for the uniaxial expansion (difference of about 20%).

Then, the damage types were characterised and the force-displacement relationship in the tested samples was analysed during the tensile test (Fig. 4). The properties of the samples with the artificial defects were compared with the properties of the reference sample.

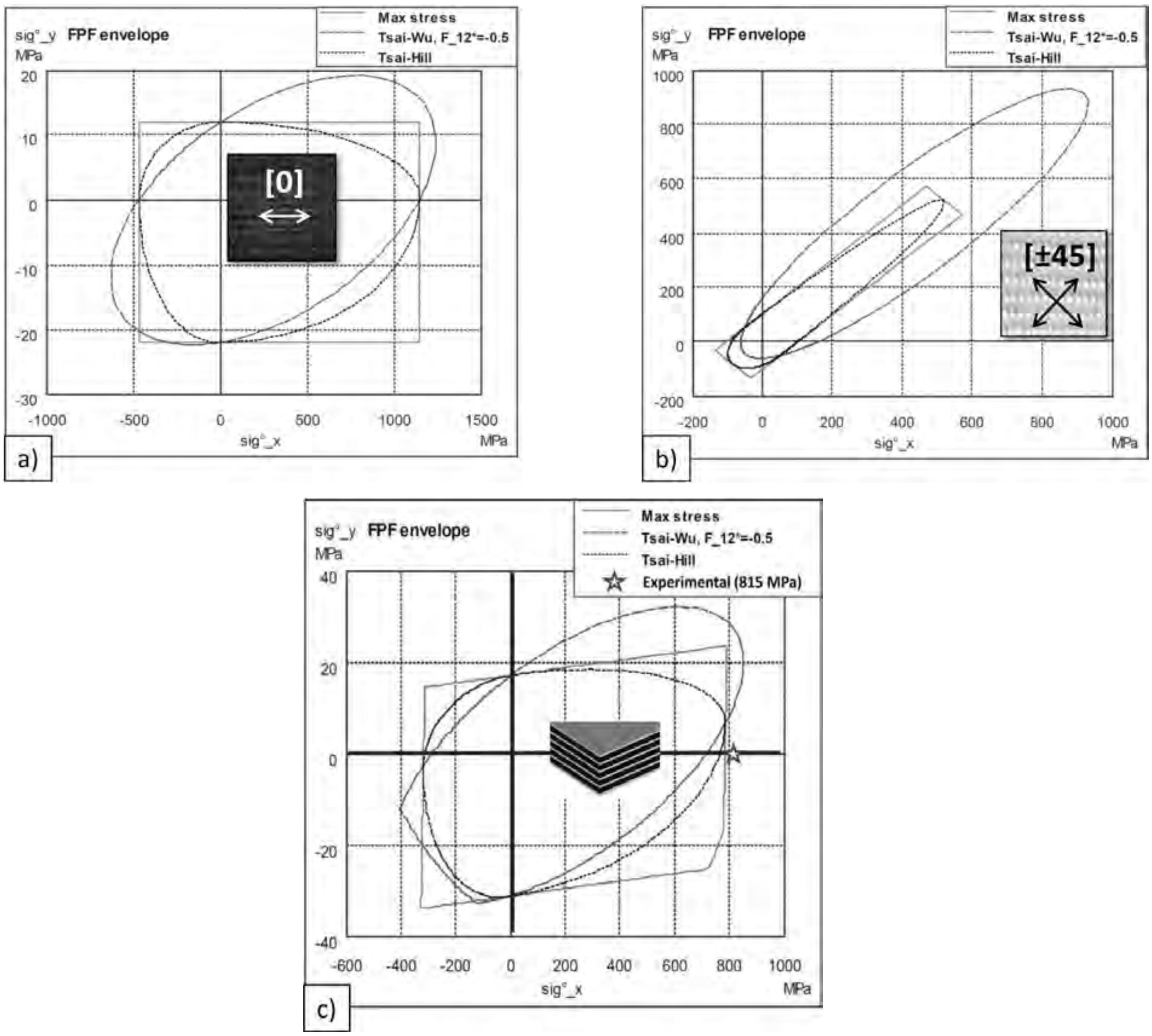

Fig. 3. FPF envelope: a) strength of carbon layer with fiber orientation angle - 0°, b) strength of glass layer with fiber orientation angle ±45°, c) load carrying capacities of GCFRP composites (16 carbon layers + 9 glass layers) compared with tensile test

Rys. 3. Obwiednia: a) wytrzymałości warstwy węglowej o kącie orientacji włókien 0°, b) wytrzymałości warstwy szklanej o kącie orientacji włókien ±45°, c) nośności laminatu GCFRP (16 warstw węglowych + 9 warstw szklanych) porównana z testem wytrzymałości na rozciąganie

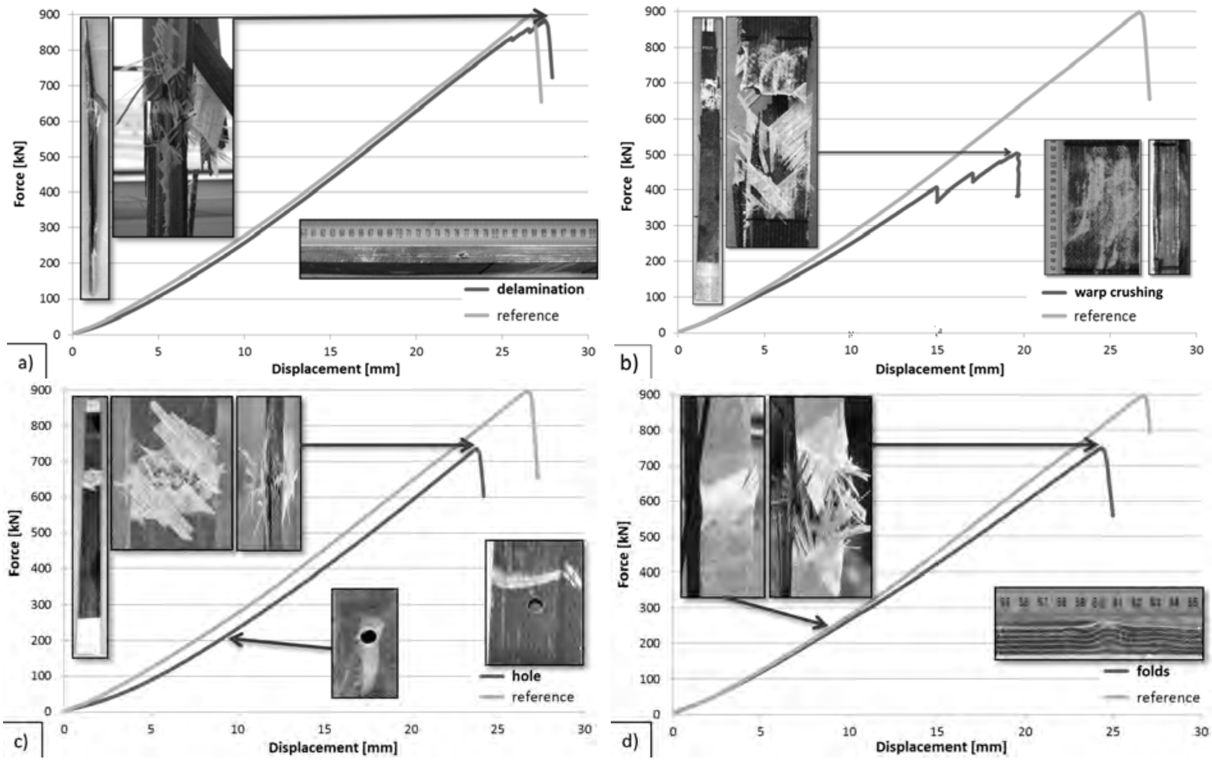

Fig. 4. Diagram of force and displacement following tensile test of samples made from GCFRP composites and their destruction forms, considering introduced defects: a) delamination, b) warp degradation, c) hole, d) fold

Rys. 4. Wykresy siła-przemieszczenie po teście wytrzymałości na rozciąganie próbek z kompozytów GCFRP oraz ich postacie destrukcji z uwzględnieniem wprowadzonych wad: a) delaminacja, b) degradacja osnowy, c) otwór, d) zafałdowanie

Delamination is the most frequent defect in the exploitation of bridge structures. The test results for delamination prove this damage form does not reduce the load-carrying capacity significantly in the static tensile test. However, it adversely affects composite durability by reducing the structure integrity evidenced in long-term deterioration of its characteristics. In the stress value discussed, delaminations propagate in the whole sample volume, shearing the fibers in the glass layers.

Another example refers to the samples with folds and holes, for which the load-carrying capacity was reduced by 20%. Such defects are especially dangerous as various damage mechanisms, in the form of fiber shearing and delaminations, are generated near the primary defects at about 25% of the laminate load-carrying capacity.

For the samples with the locally-introduced destruction in the entire sample cross-section (so-called warp crushing), a higher decrease in the load-carrying capacity was observed, amounting to 45%. In this case, the tensile load is transferred only by the carbon fibers.

It should also be noted that surpassing the critical load-carrying capacity is connected with the simultaneous breaking of carbon fibers for all the tested samples. It should be, however, claimed that the initiation and further development of damage in a GCFRP laminate under tensile load depend on the sequence of glass layers and their orientation.

The limit values of the load-carrying capacity of the tested samples are presented in Figure 5.

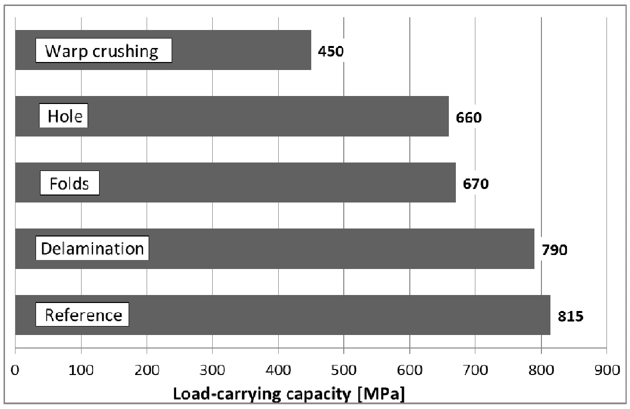

Fig. 5. Impact of damage on GCFRP load-carrying capacity under tensile load

Rys. 5. Wpływ uszkodzeń na nośność laminatu GCFRP pod obciążeniem rozciągającym

CONCLUSIONS

The experimental results related to the influence of various types of damage on the GCFRP load-carrying capacity, strength properties and engineering characteristics presented in this work, give rise to the following conclusions:

1. No significant effect of inter-layer delamination on the total longitudinal load-carrying capacity of these composites was detected for uniaxial expansion.
2. The damage propagation was found for 0.25 of the total load-carrying capacity of the tested samples near the defects (hole, fold, crushing).

3. The impact of the layered laminate damage on their strength and stiffness should be examined depending on the load (stress) and laminate quality.

Acknowledgments

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