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Augmentation of Flexural Strength of Concrete Beams Glued with Carbon Laminate

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Abstract

Improvement of performance of building objects particularly made of concrete and stone (bridges, ceilings, girders) is more and more often obtained via reinforcing with thin, high-strength bands made of carbon polymers. The reinforcement comprises gluing high-module, or high-strength thin carbon laminate (using suitable resin) to the building element at its supporting side. Additional reinforcement is obtained in result of gluing carbon laminate, having suitable orientation of fibres at the beam side planes, within shearing areas. Bending strength tests, measurements of fracturing energy and measurements of static Young's modulus were executed with the use of 500 x 26 x 26 mm concrete beams cut of the concrete B-30 blocks, made of concrete of C25/30 class, as well as with use of sandstone beams. 13.8-fold increase of bending strength, 124-fold increase of the destruction work and slight increase of Young's modulus (1.6-fold) was observed for the concrete B-30 – carbon laminate system. Reinforcement with laminate and additional reinforcement of shearing zones resulted in 17.7-fold bending strength increase (load capacity) and 187-fold increase of destruction work. Reinforcement of shearing zones of concrete beams with laminate has no influence on the system Young's modulus. Reinforcing 530 x 32 x 32 mm sandstone beams with carbon laminate results in 9.2-fold increase of bending strength and 23.2-fold increase of destruction work. Additional reinforcement of the shearing zones improved the bending strength with over 50 % and increased fracturing energy about 3 times. Analogous tests executed with the use of shorter sandstone beams proved considerably smaller values of the bending strength and destruction work. Freezing-corrosion tests with the use of concrete beams having low strength class and reinforced with laminate proved that bending strength is reduced with 60 % after 30 freezing-corrosion cycles, whereas the sandstone beams reinforced with laminate lose their bending strength with 20 % after 30 cycles.

Keywords: Concrete, Sandstone, Carbon laminate, Reinforcement of concrete beams, Mechanical properties

ZWIĘKSZENIE WYTRZYMAŁOŚCI NA ZGINANIE BELEK BETONOWYCH OKLEJANYCH ZA POMOCĄ LAMINATU WĘGLOWEGO

Poprawa właściwości eksploatacyjnych obiektów budowlanych, szczególnie tych wykonanych z betonu i kamienia (mosty, stropy, dźwigary), coraz częściej uzyskiwana jest przez wzmocnienie za pomocą cienkich, wysokowytrzymałych taśm wykonanych z polimerów węglowych. Wzmocnienie obejmuje przyklejanie wysokomodułowego lub wysokowytrzymałego cienkiego laminatu węglowego (przy wykorzystaniu odpowiedniej żywicy) do elementu budowlanego po jego stronie nośnej. Dodatkowe wzmocnienie uzyskuje się w wyniku przyklejania laminatu węglowego, mającego odpowiednią orientację włókien, w płaszczyznach bocznych belki w obszarach ścinanych. Przeprowadzono badania wytrzymałości na zginanie, pomiary energii pękania i pomiary statycznego modułu Younga w przypadku belek betonowych o wymiarach 500 x 26 x 26 mm wyciętych z betonowych bloków B-30, wykonanych z betonu C25/30, a także w przypadku belek z piaskowca. W przypadku układu beton B-30 – laminat węglowy zaobserwowano 13,8-krotny wzrost wytrzymałości na zginanie, 124-krotny wzrost pracy zniszczenia i nieznaczny wzrost modułu Younga (1,6-krotny). Wzmocnienie za pomocą laminatu i dodatkowe wzmocnienie stref ścinania doprowadziło do 17,7-krotnego wzrostu wytrzymałości na zginanie (nośność) i 187-krotnego wzrostu pracy zniszczenia. Wzmocnienie stref ścinania belek betonowych za pomocą laminatu nie miało wpływu na moduł Younga układu. Wzmacnianie belek piaskowca o wymiarach 530 x 32 x 32 mm za pomocą laminatu węglowego powoduje 9,2-krotny wzrost wytrzymałości na zginanie i 23,2-krotny wzrost pracy zniszczenia. Dodatkowe wzmocnienie stref ścinania poprawiło wytrzymałość na zginanie o ponad 50 % i zwiększyło energię pękania około 3 razy. Analogiczne badania przeprowadzone przy użyciu krótszych belek z piaskowca dowiodły znacznie mniejszej wartości wytrzymałości na zginanie i pracy zniszczenia. Badania odporności na zamrażanie-rozmrażanie belek z betonu niskiej klasy wytrzymałości, wzmocnionych laminatem dowiodły, że ich wytrzymałość na zginanie zmniejsza się o 60 % po 30 cyklach zamrażania-rozmrażania, podczas gdy w tych samych warunkach belki z piaskowca tracą 20 % swojej wytrzymałości.

Słowa kluczowe: beton, laminat węglowy, piaskowiec, wzmocnienie belek betonowych, właściwości mechaniczne

1. Introduction

Composites with polymer matrix reinforced with carbon fibres are at present more and more commonly used in various branches of industry and medicine [1]. Considerable development of the application of carbon fibres has been observed in the last decades, particularly for the needs of building and civil engineering. These applications are aimed at improvement of useful advantages of building objects, particularly concrete objects (bridges, ceilings, girders) via reinforcing the objects with thin high-strength bands made of high-strength carbon polymer composites [2-10].

Carbon laminates with polymer matrix are characterized by high tensile strength, high elasticity module, small density and large resistance to corrosive agents. A suitable type of laminate of assumed properties needed in individual applications can be easily obtained. The selection of appropriate epoxy resin used for carbon fibres bonding in the laminate, as well as for gluing the laminates with concrete elements, allows multiple improvement of load capacity of these elements, including bending strength of beams and ceilings and compression strength of columns and pillars [6-11, 12].

The concept of the reinforcement of concrete constructions with the use of composite gluing method was initiated in the nineties in some countries of Western Europe and the USA [11, 13-15]. The major advantage of this technology comprises the improvement of the construction strength and corrosion resistance, labour cost reduction, short manufacturing time, lack of size limits, and possibility of application for various bases (steel, concrete, brick, stone) [16-18]. The main disadvantage of this technology comprises a high unit price of the used composites.

The results of examinations aimed at the improvement of load capacity and value of destruction of building elements (concrete, stone) resulting from gluing to these elements laminate 1D [4, 5, 19, 20] and reinforcing the element shearing zones with the laminate, have been presented in this study. The attention was also paid to the changes of the load capacity of concrete and sandstone exposed to freezing corrosion conditions.

2. Reinforcement procedures

Reinforcement of building elements with carbon laminates comprises gluing, with the use of suitable resin, high-strength and high module thin carbon laminate with unidirectional orientation of carbon fibres 1D (Fig. 1) to the supporting side of the building element. In this way, the multiple increase of the element load capacity is obtained. This increase depends on the beam slenderness ratio. For 500 x 25 x 25 mm beams made of cement mortar CEM I with glued 0.7 mm thick laminate 1D (made of carbon fibres K63712), 13-fold increase of bending strength was obtained (Fig. 2) [21].

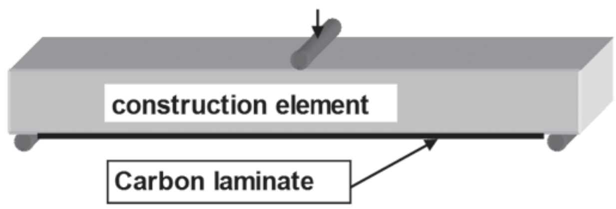

Fig. 1. Bending strength testing procedure used for beams with glued laminate.

During the three point bending of the elements reinforced with the laminate, the element destruction occurs in the vicinity of supports, *i.e.*, in the place of glued laminate ending (Fig. 3a). In some cases, a slight foliation of the laminate glued to the beam was observed. The foliation occurred as a result of the generated shearing stress (Fig. 3b). Precise gluing of the laminate endings to the beam is very important, whereas middle zones of the laminate can be slightly glued, or even not glued, because gluing quality within central zones has no influence on bending strength of laminate - building element system [20].

Reinforcement of the element zone, in which maximal shearing stresses are generated, is very important for further increase of the load capacity of building elements [22, 23]. It can be obtained via additional gluing of the suitable laminate to side planes of the element within shearing zones, *i.e.* in the vicinity of glued laminate endings, where beams usually are destroyed (Fig. 4). Gluing laminate with suitable orientation of carbon fibres within the element shearing zones considerably improves its bending strength and crushing energy, because the destruction of the beam is much more complex (Fig. 3c).

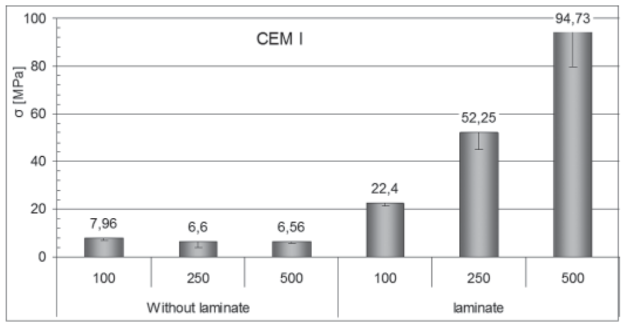

Fig. 2. Relation between beam bending strength and its length (cross-section 25 x 25 mm) - beams made of cement mortar CEM-I without reinforcement and after reinforcing with carbon laminate.

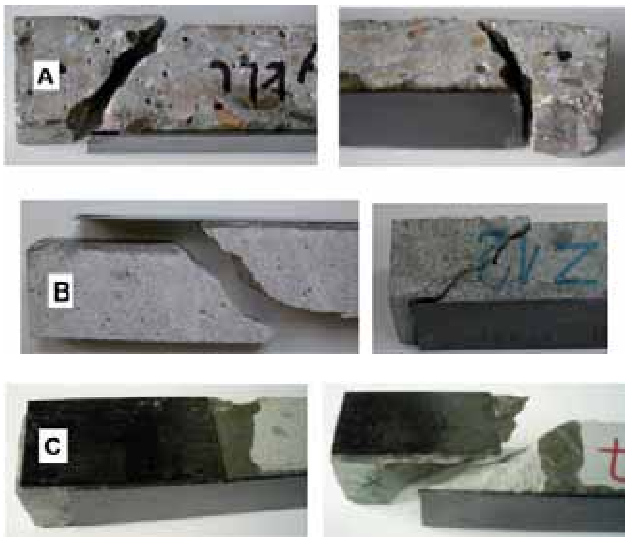

Fig. 3. The commonly used methods of destruction of laminate reinforced samples (a, b) and samples reinforced within shearing zones (c) in bending strength tests.

3. Samples and testing procedures

The tests were executed using concrete beams of strength class B-30 and C25/30, as well as with the use of sandstone beams, to which the carbon laminate with a considerable part of high-module fibres was glued.

3.1. Concrete beams

Tests on concrete reinforcement aimed at bending strength improvement were conducted with the use of 500 x 100 x 100 mm beams cut of B-30 class concrete, made of

Table 1. Properties of carbon fibers.

Properties	Type of fibers			
	K 63712	M-125 g/m^2 UTS	M-300 g/m^2 UTS	T-210 g/m^2 STS
Tensile strength [MPa]	2600	4810	4810	4400
Young module [GPa]	640	240	240	230
Elongation [%]	0.4	2	2	1.75
Density [g/cm^3]	2.12	1.8	1.8	1.78
Diameter [μm]	11.0	7.39	6.61	6.59
Longitudinal wave length [m/s]	16060	10990	10930	10920
Young module (ultrasonic) [GPa]	547	217	215	208

cement CEM III/A 32.6 N, according to the standard PN-B-06250:1988 marked as B-30, as well as beams cut of blocks of cement concrete of the strength class C25/30 marked as N/I. Concrete mixture C25/30 composed of: 45.3 % gravel 2/8 mm; 29.2 % sand 0/4 mm; 15.9 % Portland cement CEM III/A 32.5 R; 8.5 % water and 0.13 % superplasticizer – Chrysofluid CE40. Maximal grain fraction of the aggregate in concrete did not exceed 16 mm. The concrete prepared according to the standard PN-EN 206-1:2003 had compression strength σ = 37.2 MPa marked on cubical blocks of a side amounting for 150 mm according to the standard PN-EN 12390-3:2002.

The tests with use of cement concrete beams of class C 25/30 with maximal aggregate grain-size up to 31.5 mm (marked as P/I) were also executed. All concrete beams were cubicoid-shaped having the dimensions about 500 x 26 x 26 mm. Only beams N/I-g and P/I-g had the dimensions 500 x 50 x 25 mm.

3.2. Sandstone beams

Bending strength and fracturing energy tests were executed with the use of beams cut of the sandstone, which were reinforced with a gluing method at a supporting side and within shearing zones. The beams of a quadratic cross-section had the dimensions of 530 x 32.5 x 32.5 mm and 260 x 32.5 x 32.5 mm, *i.e.*, they were twice shorter than the previous ones.

3.3. Carbon laminates

Characteristics of the fibres used in the laminate is shown in Table 1. The first four values (tensile strength, Young's modulus, elongation and density) comprise the catalogue data delivered by fibre manufacturers (K63712 – Mitsubishi), whereas the two last values were determined according to a procedure presented in the work [24]. The fibre diameter was measured with the use of a projection microscope Lanametr with magnification 1000x. Laminates 1D were made according to procedure presented in the work [4, 19], saturating rowing of fibres K63712 or cloth M-300 g/m^2 with specially selected epoxy resin Epidian 601 and then pressing under high pressure.

3.4. Measuring procedure

High-modulus (E > 400 GPa) or high-strength (σ > 2.7 GPa) carbon laminate with large volume fraction of carbon fibres in epoxy resin reaching 70 % was glued to concrete and sandstone beams. Thickness of glued laminate amounted to about 0.8 mm and its length amounted to 470-490 mm (Fig. 1).

Shearing zones were reinforced with the same type of laminate. The length of laminates (plates) glued to the ends of the beams amounted to 50 mm. (Fig. 4).

The beams were tested using a three point bending method with a rate of 1 mm/min with the use of the testing machine Zwick/Roell. Spacing of supports of concrete samples amounted to L = 480 mm, and for sandstone samples 495 and 230 mm, respectively. As a result, bending strength, destruction work and statistical Young's modulus have been determined.

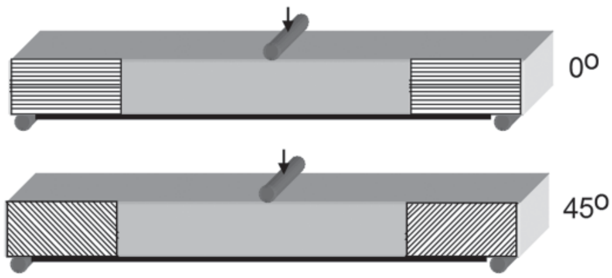

Fig. 4. Beams with glued laminate 1D and laminate 1D with orientation of fibres 0^o and 45^o reinforcement.

4. Results and discussion

4.1. Concrete beams

Strength tests with the use of the three point bending method were executed on concrete beams B-30, N/I and P/I. Testing results are presented in Fig. 5. Concrete beams N/I-g and P/I-g, which were twice longer than the other beams are characterized with considerably higher bending strength as compared to thin samples having bending strength σ = 5.9 ± 0.5 MPa. The beams of the same strength class C25/30 but containing aggregate grains having lower value of (N/I) have slightly higher bending strength than the beams containing a larger aggregate fraction (P/I). The beams made of concrete B-30 have considerably higher bending strength σ = 8.8 ± 1.4 MPa. Shorter beams $l \cong$ 250 mm made of this concrete but having the same cross-section (Fig. 5. B-30-a) have bending strength bigger by about 10 %. The beams (N/I–laminate) broken and re-glued with epoxy resin, used for gluing the laminates [19], are destroyed within the zone, which is different than the former gluing zone, and strength of such a beam is not lower than it was observed in the case of solid beam strength.

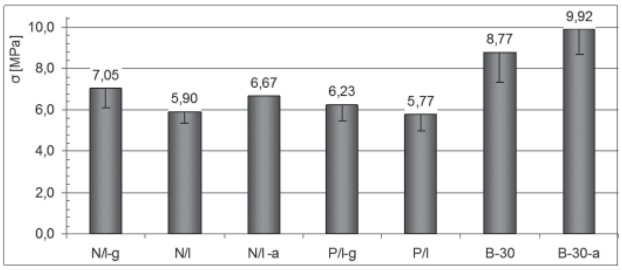

Fig. 5. Bending strength of beams made of concrete N/I, P/I and B30; beams P/I-g and N/I-g - height 50 mm; B-30-a beams B-30 recrushed (beam length - 240 mm); N/I-a broken beam glued together after breaking exposed to bending strength test.

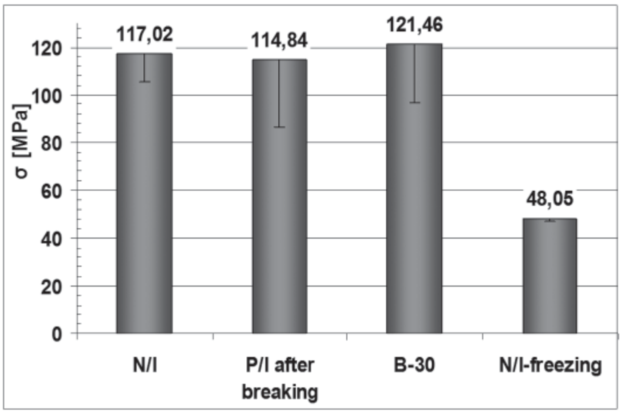

Fig. 6. Bending strength of concrete beams with glued laminate; P/I beam fracture – broken beams not glued only with glued laminate; N/I freezing - beams after 30 freezing cycles in temp down to -20°C and heet6ed up in temperature up to +40°C.

Concrete beams with glued laminate shown in Fig. 1 are characterized by several times higher strength. In the case of beams N/I made of concrete having strength class C25/30 with glued laminate, 19.0 fold increase of the strength as compared with not reinforced laminate was observed (Fig. 6). Slightly higher strength σ = 121.5 ± 24.5 MPa was proved for laminate-reinforced beams made of concrete B-30. Reinforcement of these beams was increased 13.8 times. Reinforcement with this laminate is more efficient for the concretes belonging to the lower strength class. In all cases, destruction of concrete-laminate system occurred at the end of glued laminate (Fig. 3) – without laminate tearing.

Bending strength tests were executed also on the previously broken beams. Laminate was glued to a broken beam half (Fig. 1) and a broken concrete-laminate system was exposed to bending tests. Destruction of this system was analogous as in the case of solid beams, i.e. the fracture occurred at the end of glued laminate (Fig. 3a) despite of the concrete broken in central zone. Bending strength of this system (Fig. 6 – P/I after breaking) amounted to σ = 114.8 ± 28.3 MPa, *i.e.*, analogically as in the case of the laminate – solid concrete N/I system. In bending strength tests, high compression stresses act on the laminate glued to the beam. That is why laminate ends should be properly glued to the beam, whereas gluing of central laminate zones has minor influence on strength of the laminate-concrete system.

Freeze resistance tests in corrosion conditions were conducted on beams N/I with glued laminate. Beams soaked in 5 % solution of salt NaCl were frozen for 15 hours at -20°C. Four hour defrosting was conducted also in NaCl solution, and then the beams were heated for 3 hours at +40°C. When cooled in NaCl solution, the beams were frozen for 3 hours at -20°C. 30 cycles of alternate freezing and heating beams with glued laminate were executed. Dried beams were exposed to bending strength tests, and the obtained result is shown in Fig. 6. After 30 freezing cycles, strength of beams N/I reinforced with laminate was reduced with almost 60 %. At the same time, mass of beams increased by 0.14 %. It probably resulted from the reaction between concrete constituents and solution of salt NaCl.

In order to increase the bending strength, laminate of suitable orientation of fibres (Fig. 4) should be glued to beam side planes within the fracturing zone, *i.e.*, in the vicinity of the end of glued laminate (shearing zones). The results of tests on concrete beams B-30 with glued laminate and reinforced shearing zones with laminate 1D with fibres orientation (Fig. 4, 0°C), parallel to the length of the reinforced beam are shown in Fig. 7. Gluing carbon to concrete beam B-30 resulted in 13.8 fold increase of bending strength, and reinforcement of the shearing zone results in further increase of strength by 28 %. In total, even 17.7 fold increase of strength (load capacity) of 500 x 26 x 26 mm concrete beams was obtained.

Considerably bigger changes are observed in the case of testing of destruction work of reinforced concrete beams B-30 (Fig. 7, *W*). Only gluing the laminate to the concrete beam results in 124 fold increase of the sample destruction work, and reinforcement of shearing zones resulted in 87 fold increase of the destruction work as compared to concrete without reinforcement.

Minor changes are observed in the case of examination of the influence of laminate reinforcement on Young's modulus (Fig. 7, *E*). Gluing carbon laminate to the beam resulted in only 60 % increase of the modulus value, which is changed after shearing zone reinforcing.

4.2. Sandstone beams

Bending strength tests were conducted on beams cut of sandstone and on beams reinforced with glued laminate, as well as reinforced shearing zones. Freeze resistance of a system sandstone-carbon laminate was also tested. The results of 530 mm beams (A) testing are shown in Fig. 8. Bending strength, σ, of beams with glued laminate increased 9.2 times. After 30 cycles of freezing in corrosive conditions the strength was reduced only by 20 %. Reinforcement with laminate with additional reinforcement of shearing zones caused 14.1 fold increase of the bending strength (beam load capacity).

Fracturing energy changes in dependence on the beam reinforcement are shown in Fig. 8 (*W* (A)). After gluing the carbon laminate, the sandstone beam destruction work was increased 23.2 times, and after reinforcement of shearing zones it was increased 91.5 times.

Relation between Young's modulus changes and reinforcement degree is shown in Fig. 8 (*E* (A)). After gluing

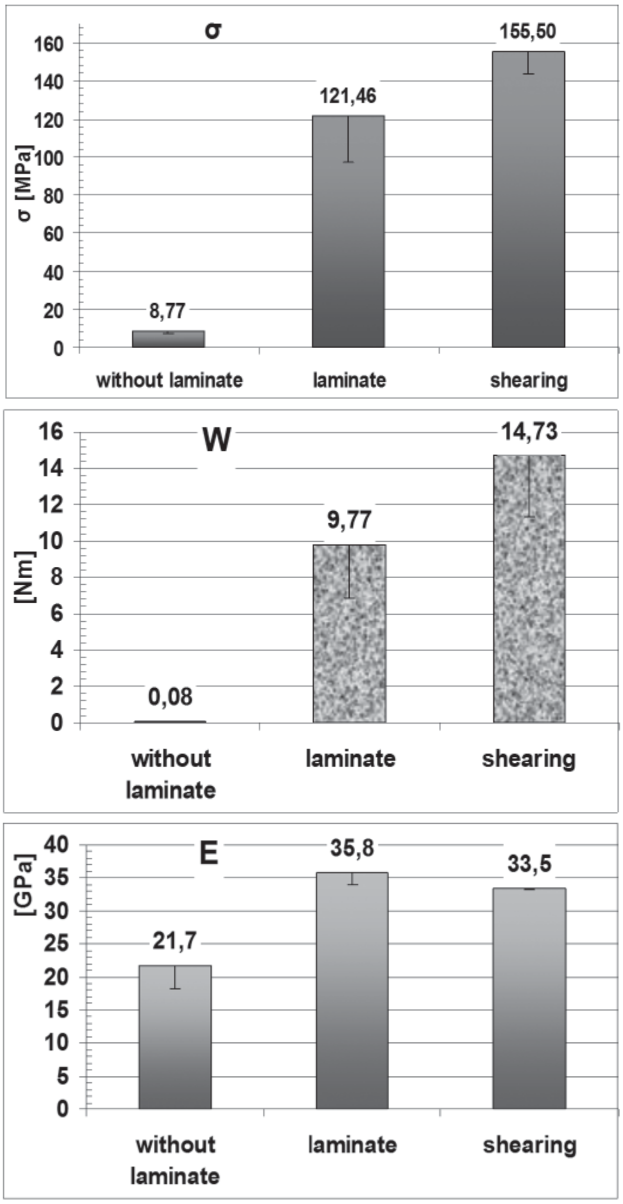

Fig. 7. Influence of reinforcement with glued laminate to concrete beams and reinforcement of shearing zones onto: σ – bending strength, W – destruction work, E – Young's modulus.

the laminate to the beam, Young's modulus of the system laminate-sandstone was increased 2.2 times.

Strength and fracturing energy tests were also executed on twice shorter sandstone beams. The results of bending strength tests are shown in Fig. 8 (σ (B)), and the results of fracturing tests in Fig. 8 (W (B)). Strength of beams reinforced with glued laminate, as well as resulting from reinforcement of shearing zones are considerably lower than it was observed in the case of twice longer beams of the same cross-section. Gluing the laminate to shorter sandstone beams increased the bending strength only 3.4 times, and after reinforcing of shearing zones, strength of the system sandstone-laminate was increased 4.6 times, *i.e.*, three times less as compared to twice longer beams. Also the work of destruction of short sandstone beams reinforced with laminate and shearing zones reinforcing was several times lower.

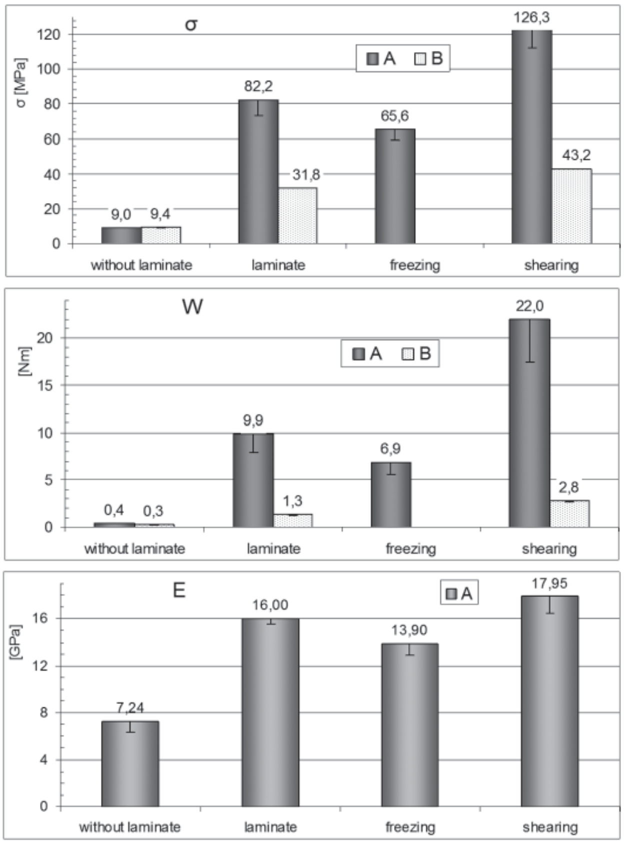

Fig. 8. Influence of reinforcement with glued laminate to sandstone and reinforcement of shearing zones onto: σ – bending strength, W – destruction work, E – Young's modulus, A – 530 mm long beams, B – 230 mm long beams.

5. Conclusions

Gluing carbon laminate to building elements at the side of tensile stress action results in multiple improvements of the element load capacity (bending strength).

A further improvement of the building element load capacity is obtained as a result of gluing the carbon laminate to shearing zones.

Improvement of the building element load capacity is better in the case of larger length / height ratio, *i.e.*, if the element is thinner.

The most effective reinforcement is obtained for elements of low strength class.

The laminate ends should be precisely glued to the beam, whereas gluing quality in the central laminate zone, or possible beam fractures, have no influence on the load capacity of the laminate-concrete system.

Reinforcement of beams reinforced with carbon laminate multiplies the amount of energy which should be delivered to destroy the system.

Gluing carbon laminate to 250 x 225 x 25 mm beams made of C25/30-class concrete improves bending strength almost 20 times, and fracturing energy over 115 times.

Reinforcement of shearing zones can additionally improve load capacity of the building element by 20 to 50 %.

Acknowledgments

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