Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 87, 2014: 25-34
(Ann. WULS - SGGW, For. and Wood Technol. 87, 2014)

Local reinforcement of naturally defected structural lumber

IZABELA BURAWSKA, PIOTR JACHOWICZ, MARCIN ZBIEĆ, MAREK GRZEŚKIEWICZ
Department of Technology and Entrepreneurship in Wood Industry, Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW

Abstract: *Local reinforcement of naturally defected structural lumber.* Paper presents local reinforcement of structural lumber, reducing negative impact of natural wood defects (especially knots), on strength parameters. Local repair engineering allows usage of structural members of decreased strength caused by natural defects, which was previously impossible because of legal regulations and risk of collapse. Strengthening procedures may also be used in existing, especially overloaded structures, renewing their initial strength and load capacity. Effectiveness of local reinforcement was determined by analysis of load capacity and deformation. Glass and carbon fibre composites were used as reinforcing materials. Various shapes of local reinforcement were tested, while maintaining constant length of strengthening in the tension zone of bent element. All tested types of reinforcement showed statistically significant increase in MOR and ultimate force. The highest strength gain was reached with X-shape reinforcement. Statistically significant MOE increase was obtained for X-shape glass fabric reinforcement (315g/m^2 and 385g/m^2 basis weight).

Keywords: timber, knots, bending, reinforcement, FRPs

1 INTRODUCTION

1.1 Timber as structural material

Wood is traditional building material, however troublesome in application. This results from its anisotropic structure and numerous structural defects. Most common defects of coniferous wood are knots, remaining of fallen of or cut-off branches. Such defect is accompanied by non-linear direction of grain.

Proprietary structure of wood directly influences its physical and mechanical properties. Despite advantageous properties of wood, like high tensile and bending strength, application of wood in structural works requires special approach and full understanding of its properties. Conforming to design regulations, knowledge and proper training provides dependability of construction and its predictable lifetime. Failing to meet above requirements has negative impact on quality of the structure, often leading to necessity of reinforcement.

1.2 Need for reinforcement

Need of reinforcement of wooden structures may occur due to various reasons. Most obvious causes are connected with natural lifecycle of construction, simple aging, misuse or unpredicted change of function of the structures.

Most common cause of reinforcement need is improper usage or design/building errors (Carolin, 2003). Such situation creates climate conditions leading to development of biological corrosion, which strongly affects mechanical properties of the structures. Figure 1 shows example of construction's lifecycle.

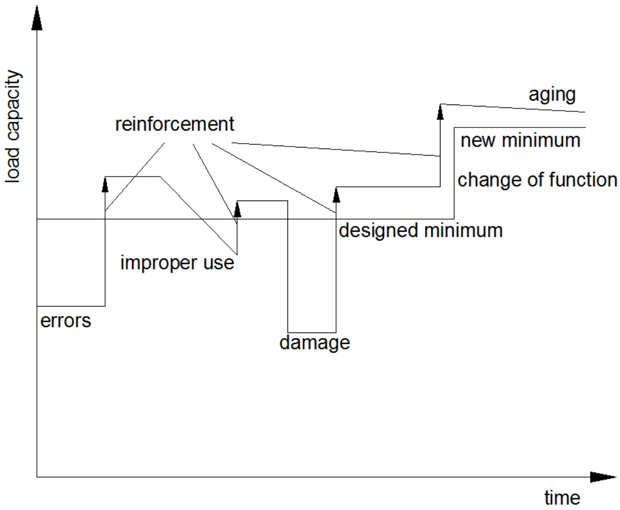

Figure 1. Exemplary lifecycle of construction

1.3 Local reinforcement techniques

Strengthening of wooden structural members by application of local reinforcement is rarely used as a repair or conservational technique. Such is caused by conservative approach of building contractors, reluctant to new techniques, unproven by many years of experience.

Until recently, in case of necessity of reinforcement of structural members, simple replacement of weakened or excessively overloaded elements, usually by new ones with larger cross-section was applied. Such activities however, are unacceptable because of preservation of physical integrity of the structure (especially historical) as well as reasonable material management.

Along with increasing technical consciousness, full-length reinforcement of structural members began to be used. Strengthening members (steel sections or rods, tie plates made of hardwood etc) are glued directly to outer faces of strengthened material or placed inside, creating internal reinforcement (Bijen, 2003; Borri, 2003; Nowak, 2007; Triantafillou, 1997). Limiting length of reinforcement, by local application reduces total costs of the procedure. This is especially important with costly composite materials, such as CFRP, one of the most expensive contemporary materials with high modulus of elasticity. Additionally, in case of historic structures, limited alteration of structure of the building are valuable from the conservational point of view.

Amongst various ideas of recovering load capacity of wooden elements, local reinforcement placed horizontally, vertically or in both planes (with respect to the local axis of the beam) may be mentioned. Local reinforcement can be hidden inside reinforced sections (in special grooves, boreholes, etc) or mounted on the surface of element. In dependence of degree of reinforcement, its placement, and length of reinforcing material, various effectiveness and fracture types are obtained. With reinforcements of excessively reduced length, reinforcement may be torn-off due to the overrun of tangent stress, delamination of composite materials may also occur.

However, with fulfilment of several requirements, local reinforcement effectiveness can be comparable to full-length one (Burawska, 2013a). It is crucial to select proper reinforcing material, regarding its strength and stiffness, provide adequate length of strengthening and determine most relevant reinforcement method (external, internal, horizontal, vertical, single or clustered).

Work proposes new method of local reinforcement of wooden structural members. Method utilizes uniquely shaped FRP composites (glass fabric, carbon sheet). Reinforcement shapes prevent creation of high concentrations of stresses, being direct cause of fracture and propagation of cracks.

2 MATERIAL AND METHODS

Testing was made with the use of pine wood, most common species in building industry in Poland. Sample groups were cut out of single board, samples were free of defects, of 20mmx20mmx300mm dimensions. Samples were weakened by a borehole of diameter equal to 25% of section height. The borehole was placed in the tension zone of bent beam, in the middle of the span. Additionally, below the hole thin layer of wood was left (1.5mm) in aim to achieve high stress concentration factor, leading to crack initiation. Weakening was aimed at simulation of a knot and unification of crack propagation in test material (Burawska, 2013b; Guindos, 2012; Bano, 2011).

Because of small dimensions of samples, less variation of strength parameters was shown, in comparison to full-scale structural lumber. Due to lack of other than simulated wood defects, determination of influence of reinforcement shape on wood strength parameters was possible.

As a reinforcing material carbon fiber mat of 200g/m2 and 400g/m2 basis weight and glass fiber cloth of 210g/m2, 315g/m2 and 385g/m2 basis weight were used. Basis weight was set only due to market availability research (most common types). Both carbon and glass fabrics were produced by Havel Composites. Four reinforcement patch types were tested: simple flat, U-shaped, I-shaped and X-shaped (Figure 2). Because of difficulties in forming, tested patch types were varied in accordance to reinforcing material. Glass fabric patch was formed as: simple flat, U-shaped, I-shaped and X-shapde. Carbon sheet reinforcements were X-shaped only. Patches were glued to test samples with Havel Composites G60 epoxy resin. Glue was dosed in amount necessary to saturate reinforcement fibres, averaging at 300g/m2.

In all cases, reinforcement was placed centrally at simulated defect, its length was set at 1/3 of reinforced element (100mm). Table 1 presents summary of types and shapes of reinforcing patches.

Table 1. Reinforcement materials types

Reinforcing material	Shape	Basis weight g/m^2
Glass fabric	Flat horizontal	210
	U-shaped	210
	I-shaped	210
	X-shaped	210
		315
		385
Carbon sheet	X-shaped	200
		400

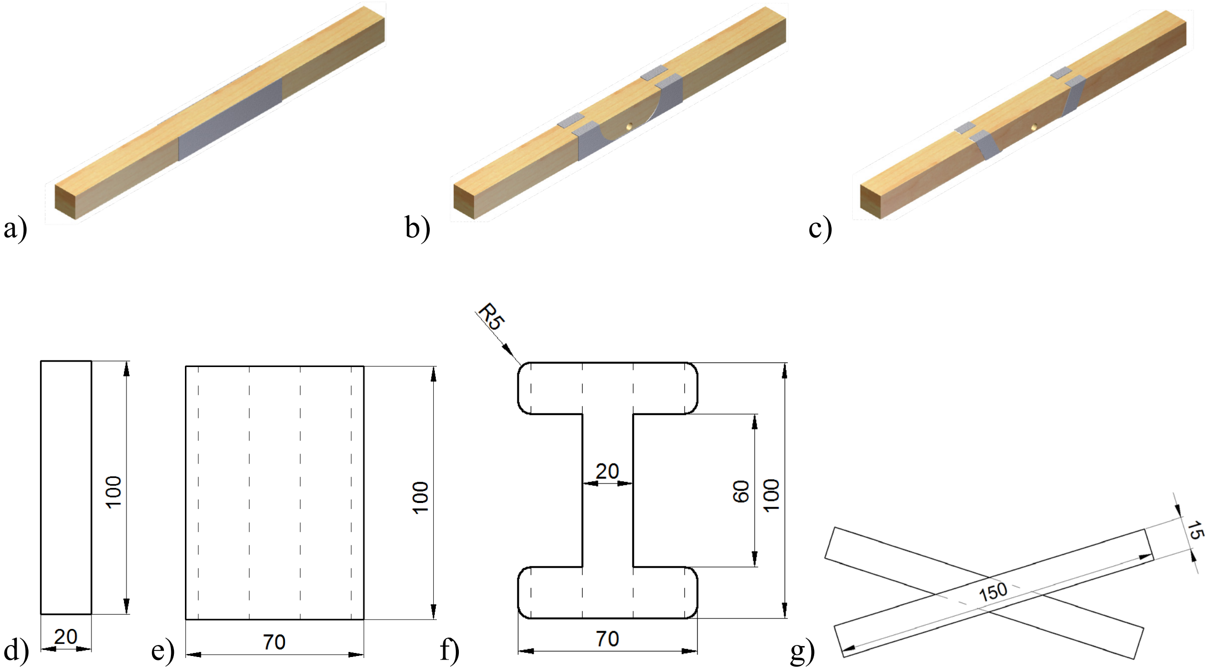

Figure 2. Shapes of local reinforcement and its dimensions, a) U-shape, b) I-shape, c) X-shape, d) flat horizontal reinforcement dimensions, e) U-shape dimensions, f) I-shape dimensions, g) X-shape dimensions

Test material was placed in Instron 3369 machine, on free support pins. All samples were three-point bend loaded and tested until destruction. Pilot tests on small specimens were designed to determine the differences between the effectiveness of strengthening utilizing various shapes of reinforcement, so four point bending tests were omitted. They are planned in the further part of the research project.

Tests were performed in accordance to the EN408:2012 standard. Data acquisition system was used during testing.

3 RESULTS AND DISCUSSION

Ten series of the samples were set for testing:

- A series – control samples, unmodified (fig. 11a),
- B series - samples weakened, no reinforcement (fig. 11b),
- C series - samples identical to B-series, reinforced by application of flat horizontal glass fabric (210 g/m2) (fig. 2 d, 11c, d),
- D series - samples identical to B-series, strengthened with U-shaped glass fabric reinforcement (210 g/m2) (fig. 2 a, e),
- E series - samples identical to B-series, strengthened with I-shaped glass fabric reinforcement (210 g/m2) (fig. 2b, f),
- F, G, H series - samples identical to B-series, strengthened by X-shaped glass fabric reinforcement (210, 315, 385 g/m2) (fig. 2 c, g)
- I, J series - samples identical to B-series, strengthened with X-shaped carbon fibre mat reinforcement (200, 400 g/m2) (fig. 2 c, g).

During the testing procedure, load and deflection were recorded. On the basis of bending tests, MOE, MOR, ultimate load and maximum deflection at destructive force were determined. Figure 3 shows MOE values obtained for samples reinforced with glass fabric, with variable shape and thickness of reinforcement.

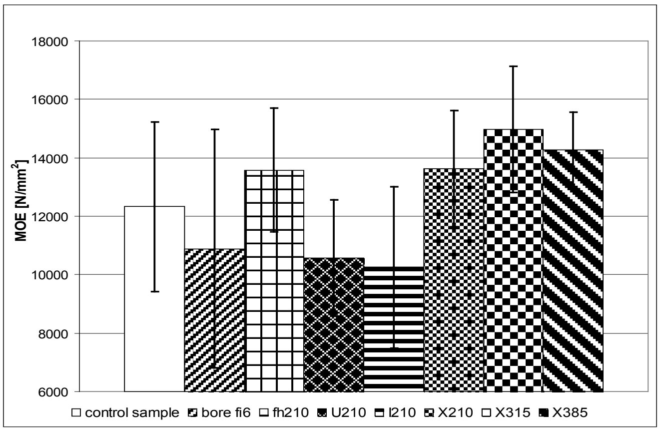

Figure 3. Modulus of elasticity of A - H series (glass fabric reinforcement)

Testing shows, that weakening of wooden member with hole of 25% of its height causes reduction of Young's modulus by 11% in comparison to sound wood. Reinforcing of tensile zone of defected bent element by simple flat strip of grass fabric (210g/m^2 basis weight) increases MOE by 25%. U-shape reinforcement however, lowers MOE by 3% in comparison to non-reinforced samples, in case of I-shape 6% drop of MOE was noticed. Highest gain of Young's modulus was showed by X-shape patch. Patch of 210g/m^2 basis weight increased MOE by 25%, 315g/m^2 and 385g/m^2 showed 37% and 31% gain, accordingly.

Figure 4 shows MOE values of samples reinforced with carbon sheet patches (XC200, XC400). Values are compared with glass fabric patches of the same shape and basis weight.

Reinforcement with carbon fiber sheet of 200g/m^2 basis weight increased MOE by 34% in comparison to non-reinforced samples. Again 400g/m^2 patch increased MOE by 35%.

Analysis showed that statistically significant (95% confidence level) MOE gain was obtained only with 315 and 385g/m^2 glass fabric X-shaped patches, and carbon fiber X-shaped mat patches.

Local reinforcement, especially made of material of low modulus of elasticity, does not increase MOE of strengthened material. Statistically significant gain in case of glass fabric patches and carbon sheet patches is most likely caused by Young's modulus of the epoxy resin, with its higher spread in case of thicker fabrics.

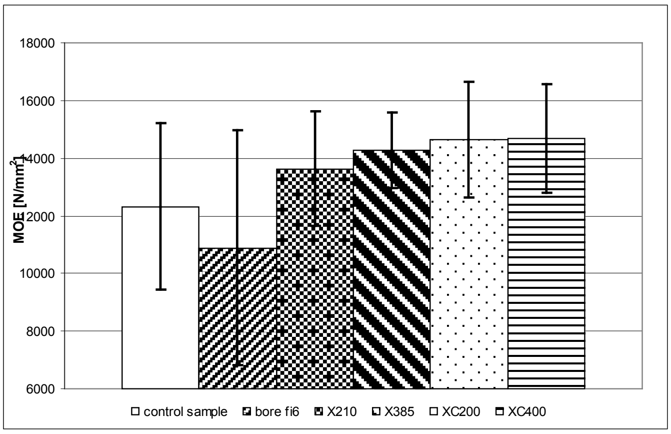

Figure 4. Modulus of elasticity of A, B, F, H, I, J series

Figure 5 shows MOR values obtained for tested samples.

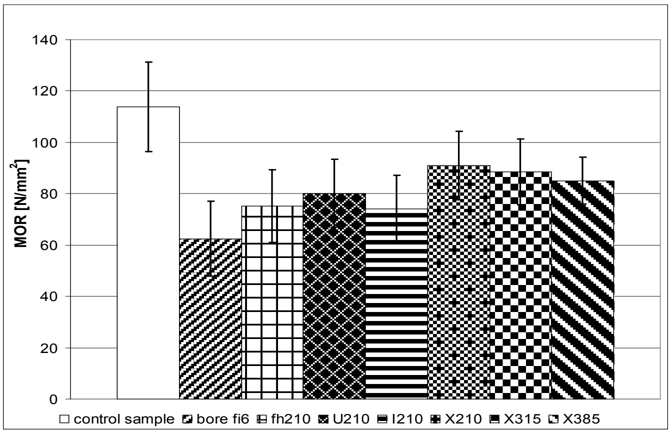

Figure 5. MOR values of A-H series (glass fabric reinforcement)

Weakening by bore of 5mm diameter caused reduction of MOR by 45% in comparison to control samples. Effect of strengthening was statistically significant in all cases. Highest MOR gain was obtained with reinforcement with X-shaped glass fabric patch of 210g/m^2 basis weight. Such application but with material of higher basis weight (315, 385g/m^2) showed lesser MOR gain. Unnecessary thickness of reinforcing patch creates higher concentration of stresses in strengthened area.

Figure 6 presents MOR values obtained by local reinforcement made of carbon patches, of 200 and 400g/m^2 basis weight. For comparison reasons, diagram includes results of reinforcement made of X-shape glass fabric patches of 210 and 385g/m^2 basis weight.

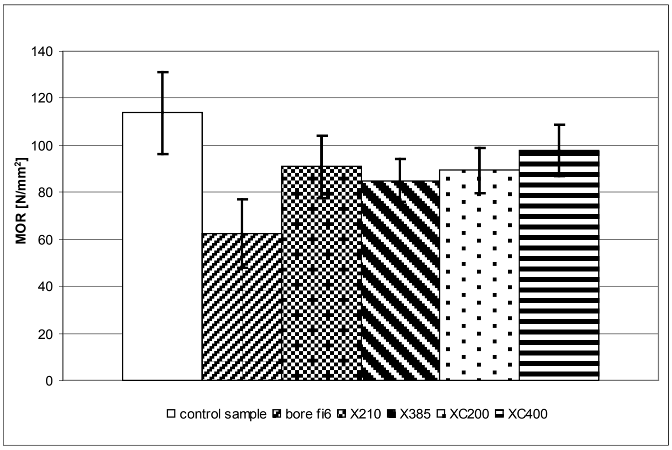

Figure 6. MOR values for carbon sheet reinforcement

The most effective reinforcement type was X-shaped carbon sheet patch, of 400g/m^2 basis weight (56% gain in comparison to weakened, unreinforced samples). Effectiveness of 210g/m^2 X-shape glass fabric patch is comparable with patches made of 200 and 400g/m^2 carbon sheet. Therefore, increased thickness and basis weight of reinforcing carbon sheets does not have significant influence on strength parameters of reinforced material.

Figure 7 and 8 shows ultimate load values obtained by application of local reinforcement in form of glass fabric patches and carbon sheet patches. All types of reinforcement caused significant increase of ultimate load capacity (95% confidence level). Testing shows, that strengthening with X-shape reinforcement causes highest increase in ultimate load capacity. The most significant increase in ultimate load values was obtained for 400 g/m^2 carbon sheet patches. Other types of reinforcement (flat horizontal, I-shaped, U-shaped) were less influencial to ultimate load.

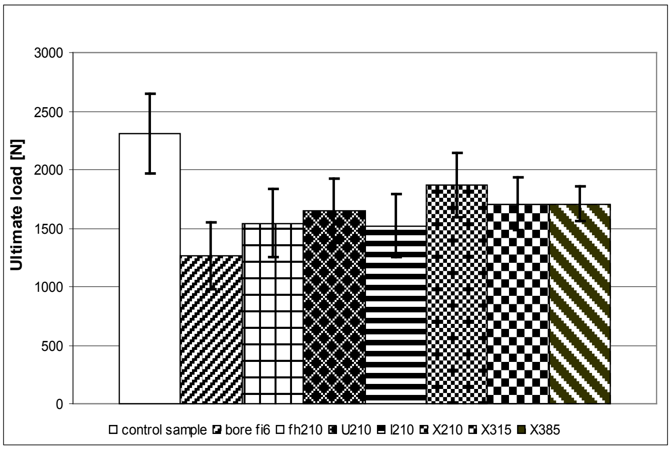

Figure 7. Ultimate load of A-H series

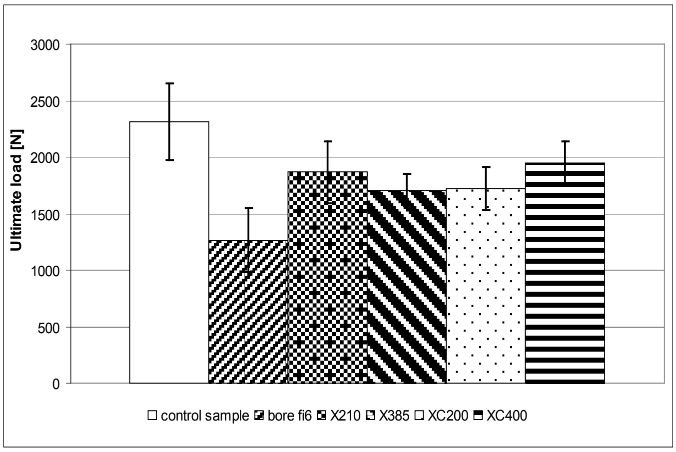

Figure 8. Ultimate load of A, B, F, H, I, J series

Figure 9 and 10 present values of deflection measured at ultimate force for samples reinforced with glass fabric and carbon sheet patches. Local reinforcement did not result in statistically significant reduction in the deflection values.

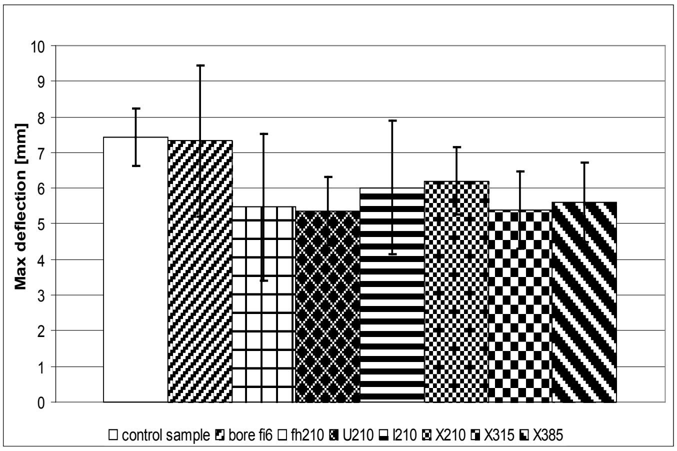

Figure 9. Deflection at ultimate load of A-H series samples

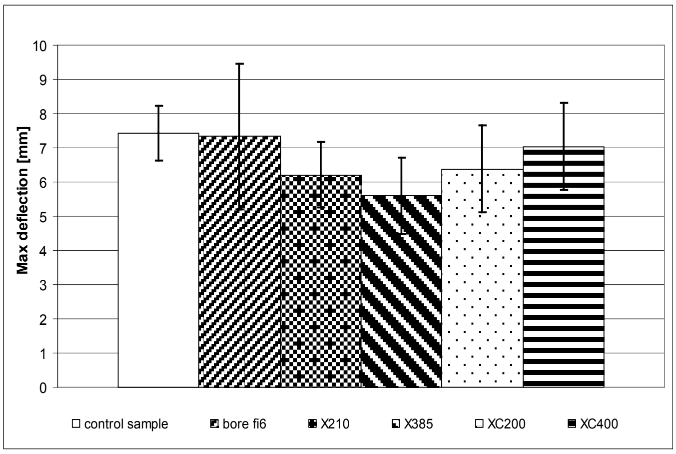

Figure 10. Deflection at ultimate load of A, B, F, H, I, J series

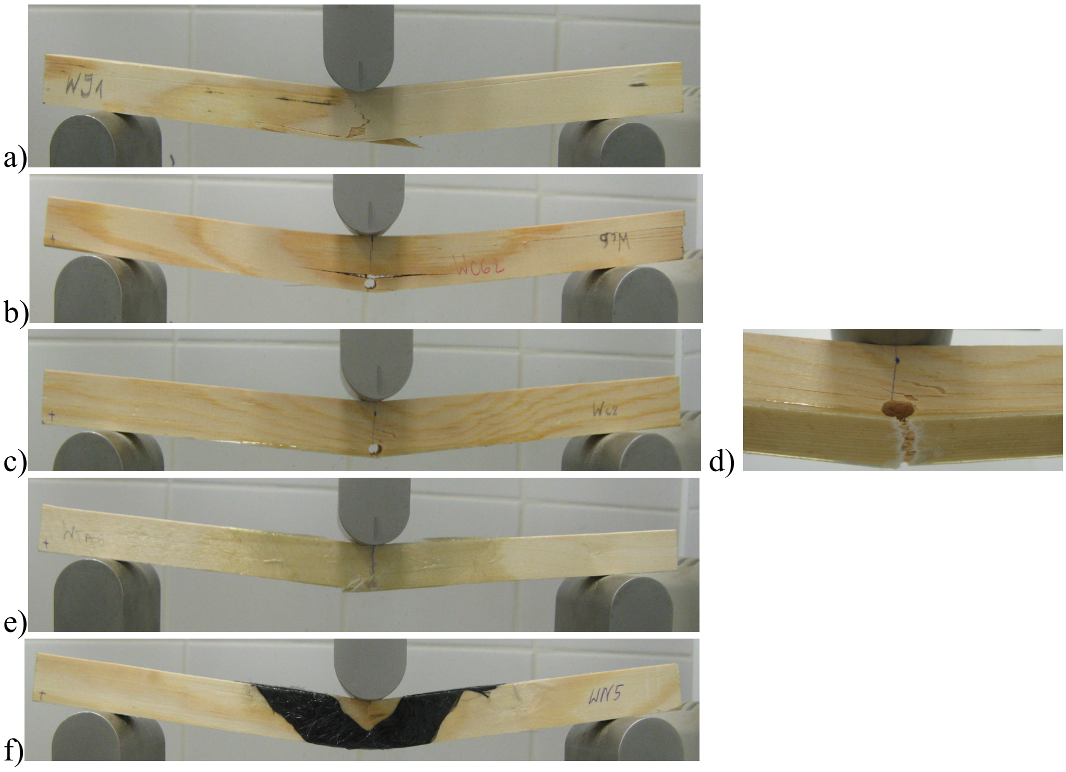

Figure 11. Characteristic type of destruction for samples of a) A-series, b) B-series, c), d) C-series, e) D-series, f) I, J-series

Typical crack for samples of B-series occurred below the hole, then proceeded through the hole and along the grain. In case of C-series, reinforced with simple flat glass sheet reinforcement, crack initiation occurred also below the hole, but the ultimate force was significantly higher than in case of B-series samples. Samples strengthened with I-shaped, U-shaped and X-shaped reinforcement (fig. 11e, f) showed displaced crack initiation, due to exceeding shear stress capacity of carbon and glass patches. Crack initiation was moved beyond the weakened, critical zone.

4 CONCLUSIONS

Local reinforcement of wooden structural members does have positive impact on their strength, and can be regarded as justified. Local reinforcement provides economically better utilization of materials than full-length one, providing possibility of significant savings.

Local reinforcement results in more favourable stress distribution and reduction of stress concentration factor in areas exposed to crack initiation. Location of crack moves beyond the weakened zone. Rupture occurs as a result of exceeding the shear stress capacity.

X-shaped reinforcement is most appropriate for timber strength enhancement.

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Streszczenie: *Lokalne wzmocnienie naturalnie osłabionego drewna konstrukcyjnego.* W pracy przedstawiono lokalne wzmocnienie drewna konstrukcyjnego, redukujące negatywny wpływ naturalnych wad drewna (zwłaszcza sęków) na parametry wytrzymałościowe. Lokalna technika naprawcza pozwala na wykorzystanie elementów konstrukcyjnych o zmniejszonej wskutek występowania wad wytrzymałości, co było wcześniej niemożliwe ze względu na przepisy prawne i ryzyko uszkodzenia konstrukcji. Technika wzmocnienia może być również stosowana w przypadku konstrukcji istniejących, a szczególnie nadmiernie wytężonych. Efektywność miejscowego wzmocnienia została określona poprzez analizę nośności i odkształcenia. Kompozyty na bazie włókien szklanych i węglowych zostały zastosowane jako materiały wzmacniające. Różne kształty lokalnego wzmocnienia były poddane analizie, przy zachowaniu stałej długości wzmocnienia w strefie rozciąganej zginanych elementów. Zastosowanie wszystkich typów wzmocnienia wykazało statystycznie istotny wzrost nośności i wytrzymałości na zginanie. Największy wzrost wytrzymałości odnotowano dla X-kształtnego zbrojenia. Również statystycznie istotny wzrost MOE został otrzymany w przypadku wzmocnienia X-kształtnym zbrojeniem wykonanym z wykorzystaniem włókna szklanego (gramatura 315g/m^2 and 385g/m^2).

Corresponding author:

Izabela Burawska
Department of Technology and Entrepreneurship in Wood Industry,
Faculty of Wood Technology,
Warsaw University of Life Sciences – SGGW,
159 Nowoursynowska St., B. 34,
Poland
email: izaburawska@gmail.com