Strengthening of Bent Timber Beams in Historical Objects

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1. Introduction

In wooden structures, timber ceilings are most susceptible to destruction. They also most frequently require repair and reinforcement. These ceilings are often substituted with new technical solutions in the form of, for example, ceilings on steel beams or ceilings of reinforced concrete. In predominating number of cases, decisions on elimination of traditional solutions are too hasty – beams which after reinforcement could fulfill the requirements associated with new function of the object, are dismounted.

Technological development of composites of fibre reinforced plastics (FRP) cause them to be ever increasingly utilized for reinforcing timber elements providing the elements greater load capacity, rigidity and more unified structure in comparison with conventional non-reinforced elements. Besides, these new materials can serve to reinforce elements that are in bad technical state (historical objects), [1].

The advantages of reinforcing with strips of carbon-fibre reinforced plastics (CFRP) are revealed particularly in conservation of historical objects. The primary concern here is proportion of weight and dimensions to strength obtained. The strips can also be easily "concealed" in the section to retain the original appearance of the element. Thermal conductivity of composites is considerably lower than that of steel which simultaneously makes flame resistance of the structure using them to be greater.

Methods of reinforcement proposed in literature are as a rule unacceptable in conservatory applications – the strips were usually glued onto external planes of elements as in concrete structures. In historical objects, due to the fact that we are often concerned with rich decor of ceilings, the appropriate solution is "immersing" the strips into the wooden section. This enables utilizing the method in conservatory works, [2]. This also limits the possibility of delamination of glued "strip-wood" joint, [3].

In bent elements, the deciding factor regarding load capacity is, as a rule, the stretched zone of the section. Timber defects in the stretched zone to a significantly larger extent lower the load capacity of the element than in the compressed zone. One of the methods of reinforcing it is to glue in reinforcement, e.g. steel rods and sheets, GR rods or FRP strips. Joining of reinforcement with wood is done first of all by means of epoxy adhesive compositions.

2. Results of experimental tests

Subject of testing was application of CFRP strips for reinforcing bent timber beams of historical objects. Proposed in the research program was utilization of carbon strips for reinforcement and regeneration of load capacity of beams with defects – biocorrosion, inclusions, grain slope and cracking of wood.

The testing station is presented in Fig. 1. Beams in technical scale of length 4 m and cross section 12x22 cm were supported freely at both ends. Beam span in support axes amounted to 3.80 m. They were loaded symmetrically with two-point force by means of which pure bending was obtained in middle part of the beams. Forked supporting was used on the supports to prevent loss of flexural stability (lateral buckling). A PC and multi-channel measuring system UPM 100 of Hottinger Baldwin Messtechnik were used to record the results.

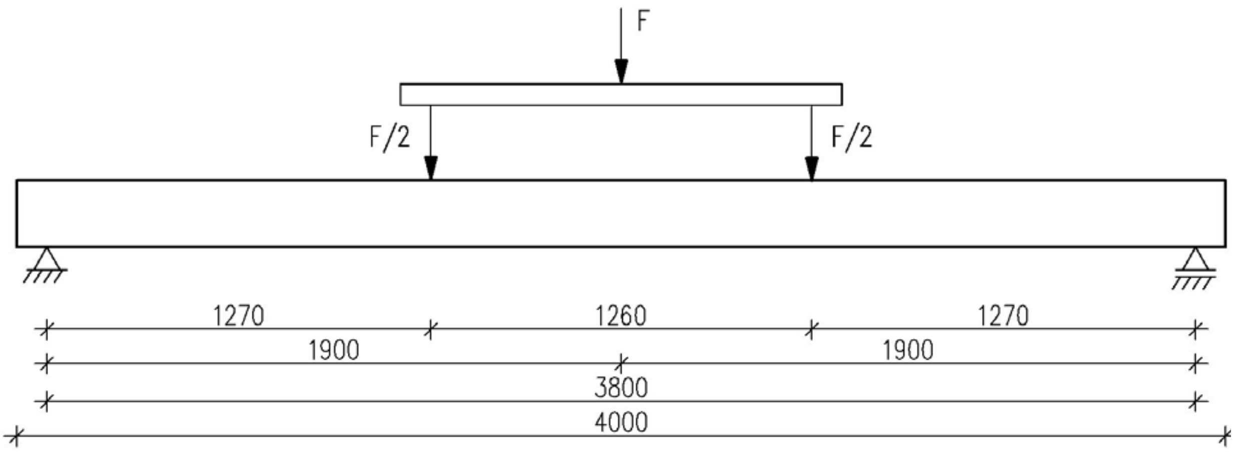

Figure. 1 Testing station diagram

Subjected to testing were 18 numbers of about 100-year-old pine beams (6 types of 3 beams each in series: A, B, C, D and E) and 3 beams of new wood (series G):

- beam A – witness beam of old wood,
- beam B – reinforced beam, with one CFRP strip glued in vertical system along full length of beam; cracking of wood simulated over full length by means of asymmetrical slits 4 mm wide and 25 mm deep;
- beam C – beam with removed corroded part replaced with wooden inserts and with two CFRP strips glued in vertical system along full length of beam;
- beam D – beam reinforced with two CFRP strips glued in vertical system along full length of beam; non-uniform course of fibres simulated by means of slits on both sides of 3 mm width and 20 mm depth;
- beam E – beam reinforced with two CFRP strips glued in vertical system along full length of beam; grain slope simulated by means of 3 slits of 3 mm width and 20 mm depth in system not parallel to longitudinal edge of beam;
- beam F – beam reinforced in zone of maximum bending moment by means of three CFRP strips of lengths from 400 to 600 mm, in horizontal system; weakening of stretched zone simulated by means of cut out hole of diameter 25 mm;
- beam G – witness beam of new wood.

Cross sections of tested models are shown in Fig. 2, whereas zone of maximum bending moment in beam F is shown in Fig. 3.

Thickness of CFK S&P strips used amounts to 1.2 mm, width 50 mm. Used for gluing the strips was two-component adhesive on epoxy resin base for S&P composite mats Resin 55 (because of consistency enabling gluing of reinforcing inserts inside the section). Filling up of slit sections in beams B, C, D and E after gluing the strips was done with adhesive composition of Resin 55 and quartz flour in ratio of 100:80 by weight.

Shown in Fig. 4 are values of destructive forces for all the beams tested (horizontal broken line indicates mean value of destructive force for witness beams of series A), whereas Table 1 shows mean values of destructive force for each of the series as well as percentage growth of load capacity with respect to the series of non-reinforced beams – A. Growth of load capacity of tested elements reinforced with CFRP strips is significant, amounting from 21% for beams of series F to slightly over 79% for beams of series D. Visible however is rather large spread between values of destructive forces for individual models particularly for beams of series B, C and D for which the maximum and minimum values among three trials differ from each other by 35-48%. However, on the examples of non-reinforced beams of old as well as new wood (series A and G), where the difference between extreme values amounts to about 30%, clearly visible are differences in load capacities resulting from different wood structures and influence of defects. Results for series F are very close to each other which for full-dimension solid timber sections should be considered as exceptional.

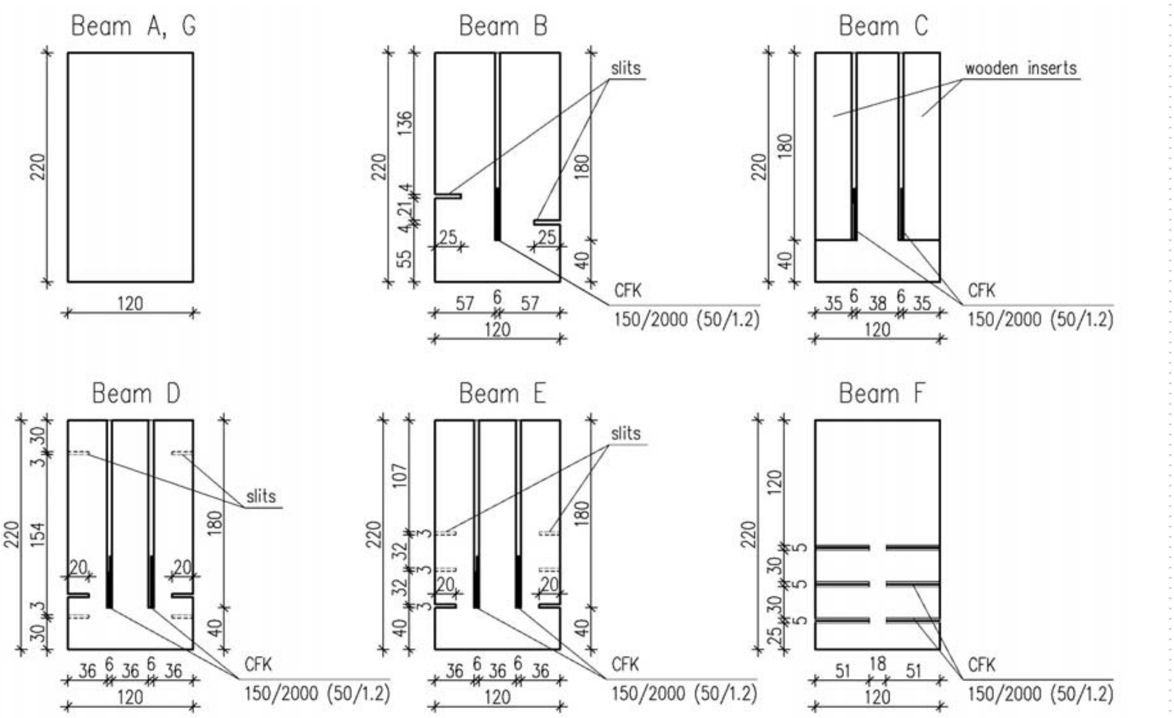

Figure 2. Cross sections of tested beams

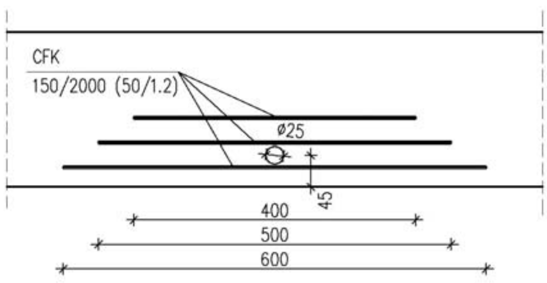

Figure 3. Maximum bending moment zone of beam F, side view

Table 1. Mean values of destructive force for each series as well as growth of load capacity with respect to beams without reinforcement

		Beam series A	B	C	D	E	F	G
Mean destructive force	[kN]	30.91	44.01	52.82	55.42	49.17	37.39	51.49
Growth of load capacity	[%]	-	42.4	70.9	79.3	59.1	21.0	-

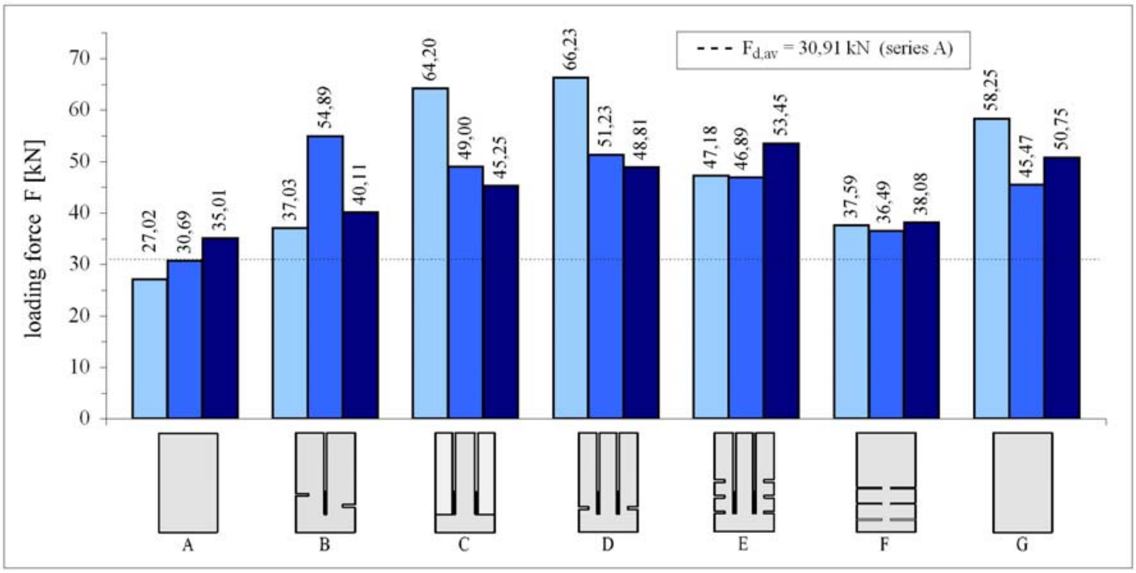

Figure 4. Values of destructive force of tested elements

Presented in drawings 5-8 is part of test results obtained for beams B and F. Shown on the presented paths of static equilibrium, for comparison, line of trend for three tested witness beams A and limiting deflection L/250 for ceilings and L/167, that is increased by 50% for old, renovated objects, indicated by vertical lines, according to [4]. Values of stresses in strip were calculated on the basis of deformations determined by readings of electric-resistance wire strain gauges at half the height of strip. Form of destruction of tested beams is shown in Figs. 9 and 10.

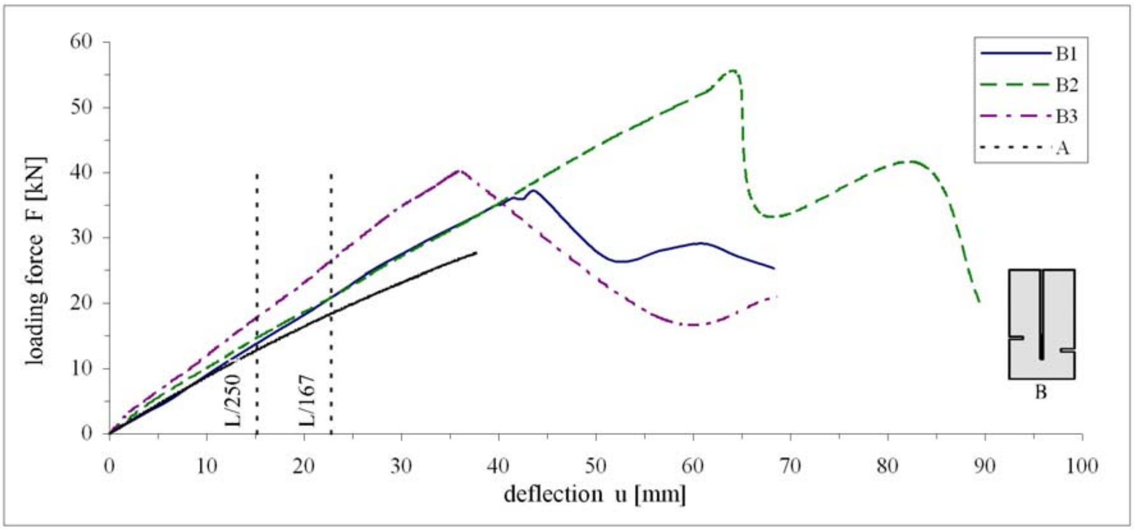

Figure 5. Equilibrium paths series B beams

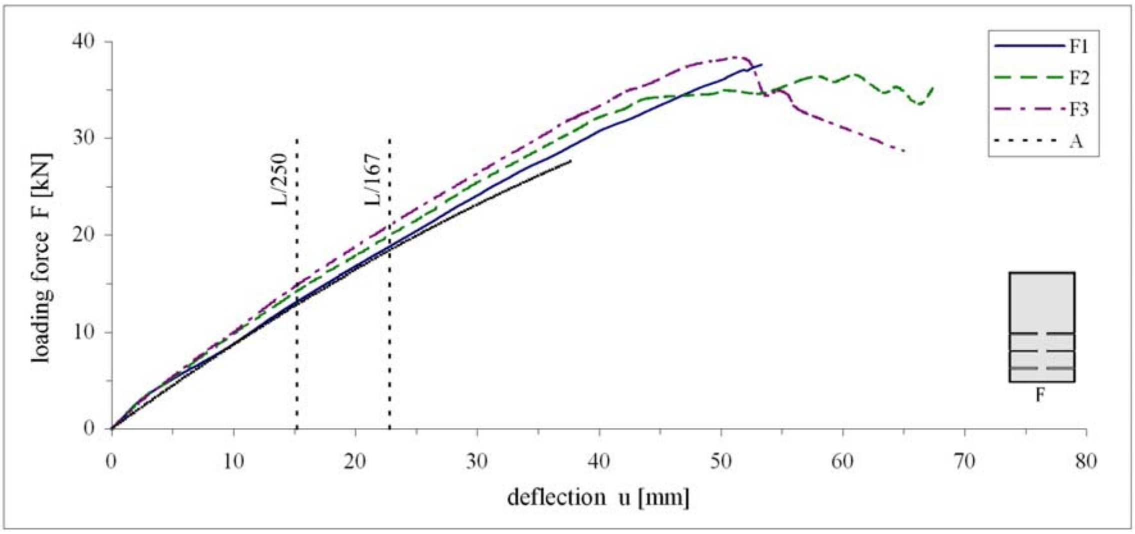

Figure 6. Equilibrium paths of series F beams

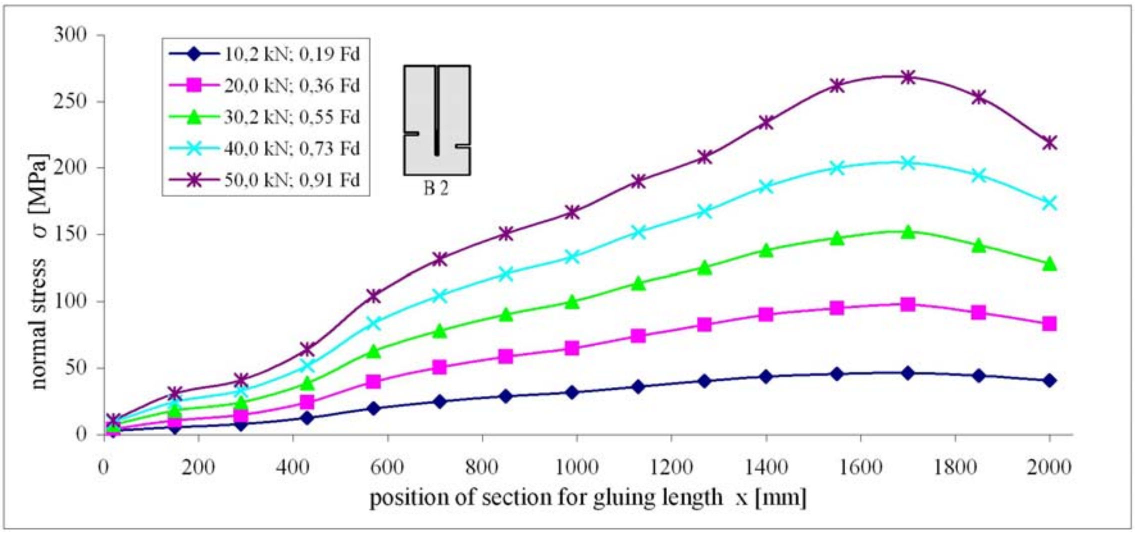

Figure 7. Normal stresses of strip – beam ***B2***

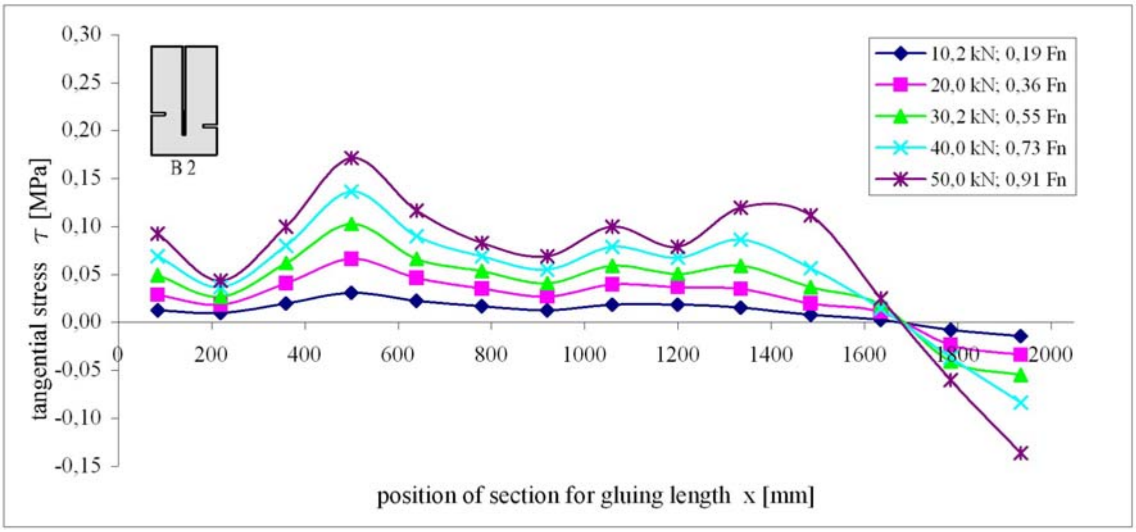

Figure 8. Tangential stress in joint – strip in beam B2

Figure 9. Form of destruction of beam B2

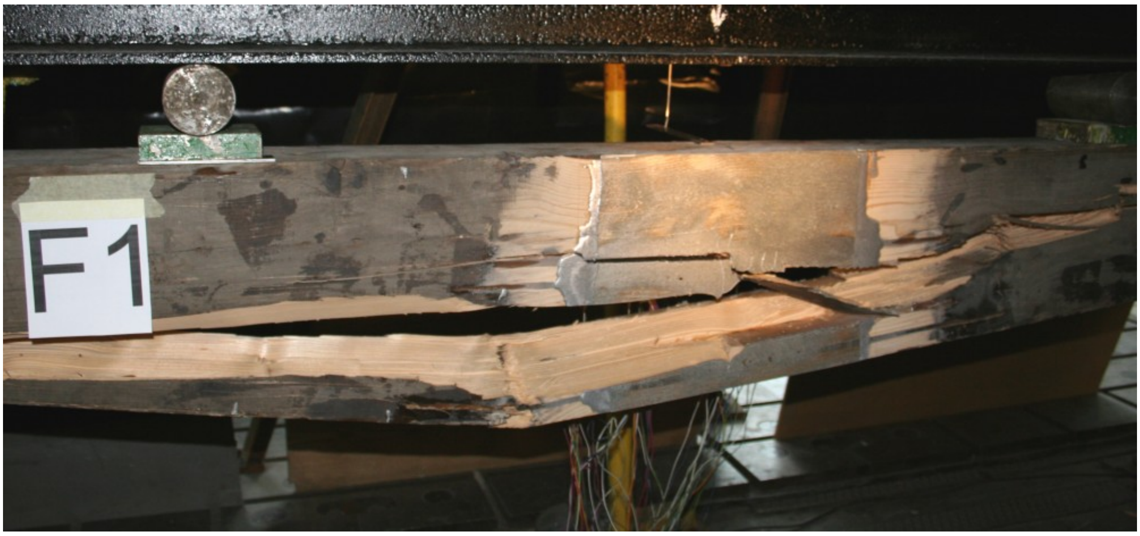

Figure 10. Form of destruction of beam F1

Besides traditional measuring methods (electric-resistance and induction sensors) for measuring deformations of reinforced sections (combined), attempt was made to apply photo-elastic method of surface layer. So far, such attempt has not been described in relevant literature. The method requires conducting further tests aimed at verifying consistency with measurements by traditional methods. All test were made in Laboratory of Institute of Building of Wrocław University of technology. Photo-elasticity tests were made under supervision of dr. Ludomir Jankowski. Presented in Figs. 11 and 12 is total isochromatic image along with values of deformations obtained for beam F2.

On the basis of testing results obtained (for beams of all series), it can be stated that photo-elasticity reflects timber structure well - often occurring in wood are cracks, defects, nail holes, possibly places where joints occur (wooden pins, bolts, nails, etc.)

Thanks to gluing of layer in places of non-continuity of section (slit), disturbance is observed in course of deformation graph due to occurrence of tangential stresses, which can in no way be obtained depending only on the method of measuring by means of electric-resistance wire strain gauges, since this measurement has quasi-point character.

Differences between values of deformation obtained by strain gauges and photo-elastic methods can be explained by differences in structures of two opposite side surfaces of beams - different courses of timber fibres, fibre concentrations, structural cracks and occurrences of inclusions (knots). There is no way of obtaining timber beams of section dimensions as in the tests (120 x 220 mm) of ideally parallel course of fibres from two sides.

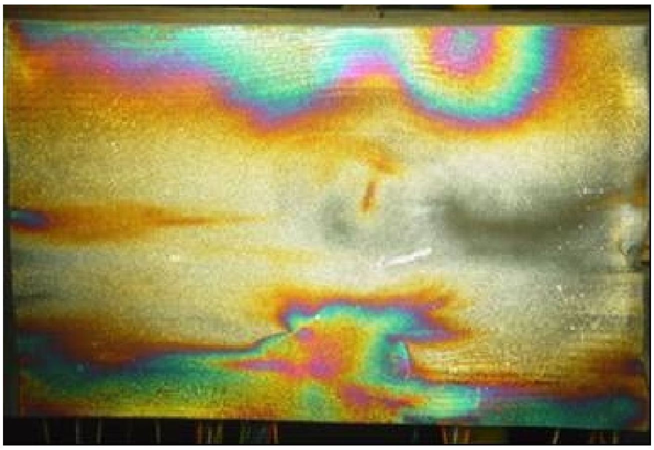

Figure 11. Total isochromatic image – beam F2 (F = 30 kN)

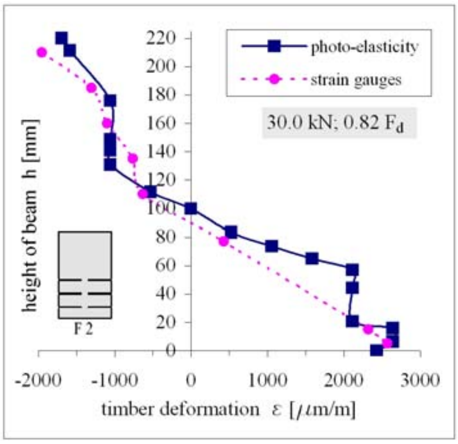

Figure 12. Timber deformation in bent section – beam F2 (F = 30 kN)

3. Numerical testing

Numerical calculations by means of finite element method were performed in Standard ABAQUS 6.5 environment module, [5]. This packet provides the possibility of three-dimensional analysis in the scope of flexible-plastic elements of orthotropic material and additionally solving of contact problem.

8 models were subjected to analysis: 4 beams (A, B, C and F), with two different models of woodworking:

- model 1 – working of wood, adhesive and strip in elastic scope,
- model 2 – working of wood in flexible-plastic scope taking into consideration Hill's criterion of anisotropic plasticity, [6]; working of adhesive and strip in elastic scope.

Utilized in the calculations was symmetry of tested beams for reducing the number of finite elements, parts cut off were substituted by disabling corresponding displacements and angles of rotation. Analysis was performed on half the length of beam B (one axis of symmetry, non-symmetrical slits from two sides), and 1/4 beam F (two axes of symmetry).

Wood as well as adhesive was modelled by means of eight-nodal spatial elements of symbol C3D8, whereas inserts in the form of composite CFRP strips by means of four-nodal coated elements of symbol S4. The number of elements and nodes that individual models consist of are shown in Table 2.

Continuity of displacement was provided/assumed at the borders of layers. For modeling of contact, "tie" option was used, which equalizes displacements given the contact surfaces.

Table 2. Number of elements and nodes of models analyzed

model	beam B	beam F
number of elements	22 565	27 456
number of nodes	25 864	32 301

Material numerical constants utilized in the analysis are presented in Table 3 whereas yield points are presented in Table 4.

Table 3. Material parameters of wood and CFRP strip

	Young's modulus ***E*** [MPa]			Poisson's ratio ***υ*** [-]			Modulus of rigidity ***G*** [MPa]		
	E_x	E_y	E_z	υ_{xy}	υ_{xz}	υ_{yz}	G_{xy}	G_{xz}	G_{yz}
Wood	8000	400	400	0.37	0.42	0.47	570	570	57
CFRP strip	165000	10000	10000	0.3	0.3	0.03	5000	5000	500
Adhesive		2500			0.3			-	

Table 4. Yield points assumed for analysis

Yield points [MPa]						
σ_{11}	σ_{22}	σ_{33}	σ_{12}	σ_{13}	σ_{23}	σ^0
15.5	3.6	3.6	6.0	6.0	3.0	15.5

Due to the examined case of strength - bending, model 2, in which influence of plastic deformations is less than in cases where pressure zones occur (e.g. compression in joints of wooden rods of timber structures), seems to be an imperfect model. Inasmuch as in case of beam F (Fig. 14) good correlation was obtained with experimental results, in case of model B (Fig. 13) exhaustion of the beam's load capacity occurred too quickly. The model assumes plasticizing of tension zone which in reality does not occur. In further numerical testing/examinations, it might be advisable to create a model taking into account brittle cracking of wood in the tension zone.

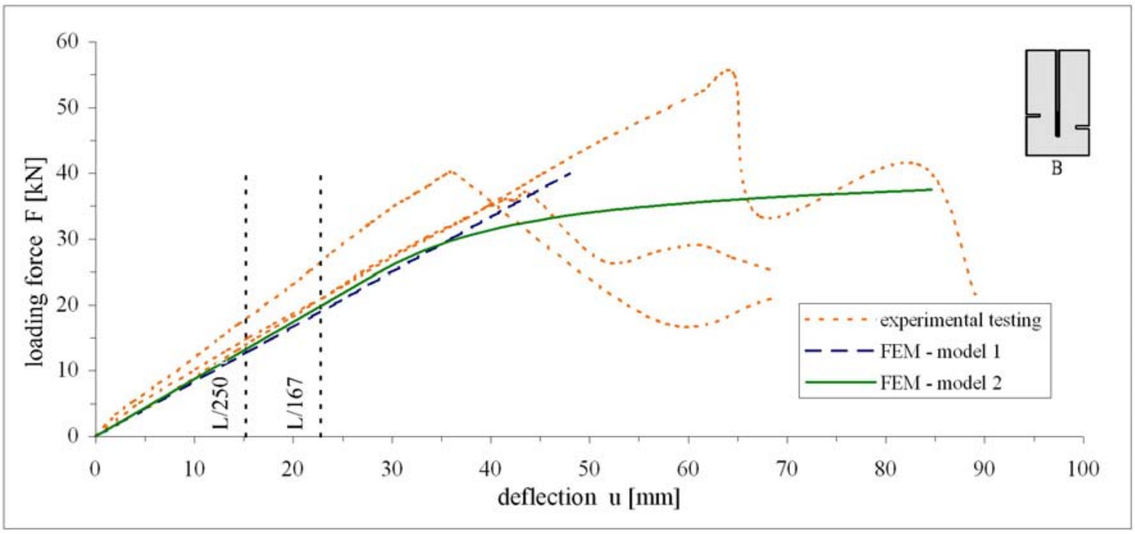

Figure 13. Relationship of "F" for experimental models and numerical testing, beam

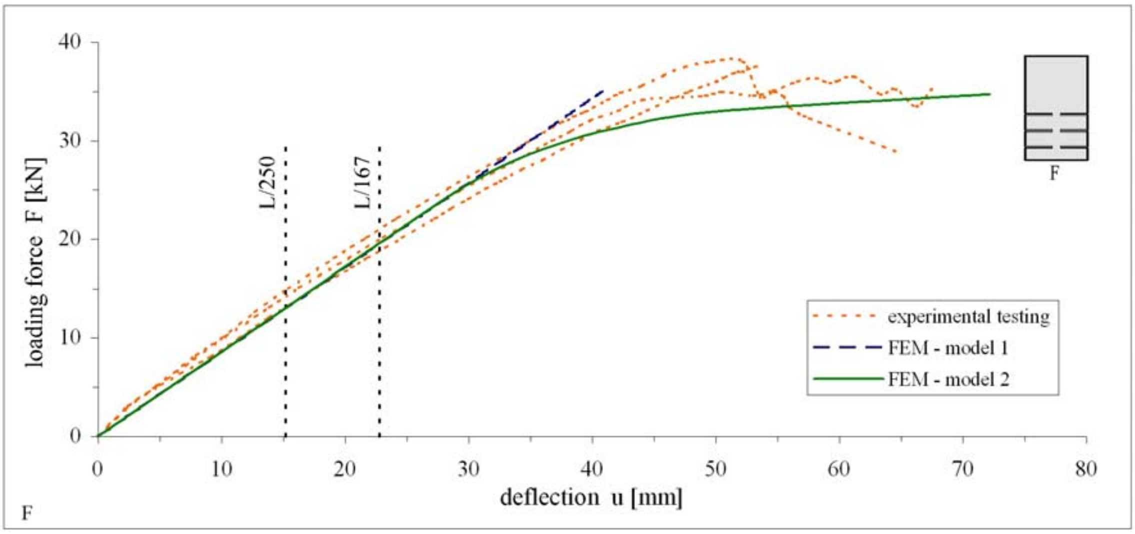

Figure 14. Relationship of "F" for experimental models and numerical testing, beam F

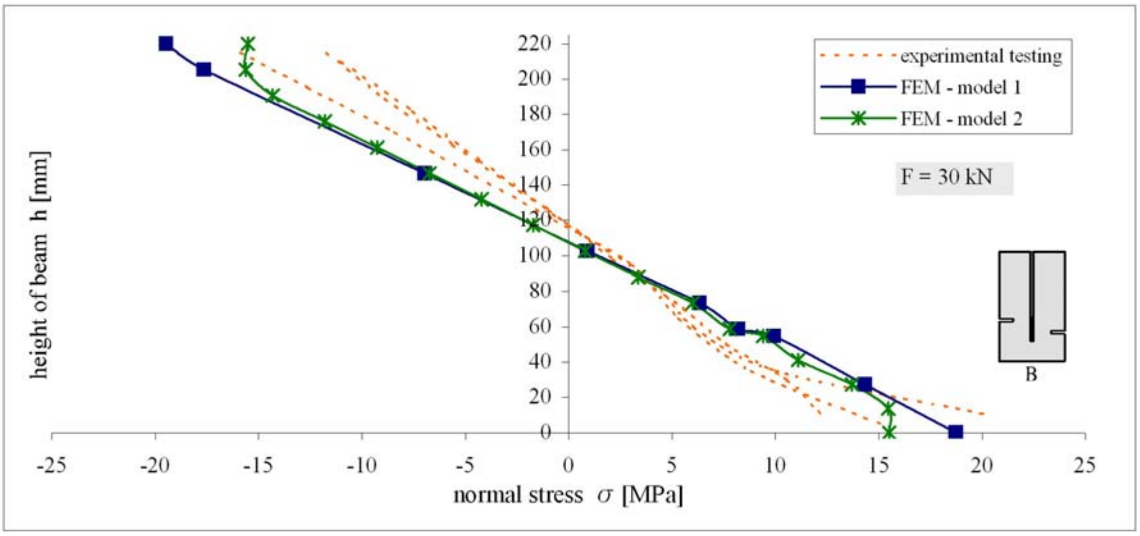

Figure 15. Graph of normal stresses in wood in beam B, force F = 30

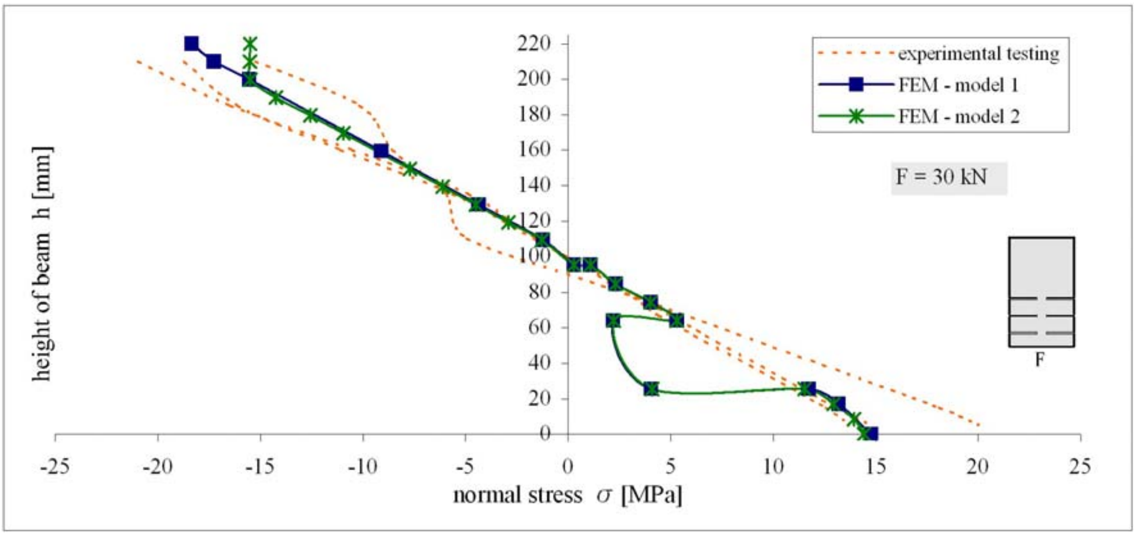

Figure 16. Graph of normal stresses in wood in beam F, force F = 30 kN

Very good correlation, in the scope of normal stresses in wood σ_x, was obtained for beam F - Fig. 16. Moreover, the stress pattern obtained in numerical analysis is of similar character to strain pattern obtained in photo-elastic tests (Fig. 12) - "peak" at height of CFRP inserts, which is not visible in graphs of deformations/strain obtained on the basis of readings of electric-resistance wire strain gauges.

The assumption that wood is homogeneous material is simplification, taking into consideration all the mentioned material defects of wood in averaged manner. In bent beams, presence of material defects of wood in tension zone is particularly significant. Analysis of wood (in technical scale, building wood) as anisotropic material is practically impossible - orientation of axes *y* and *z* is almost always precluded. Whereas taking wood as isotropic material is too large a simplification. Treating wood as orthotropic material is sufficient approximation for numerical analysis.

Numerical analysis showed a slightly lesser increase in rigidity of reinforced models than in experimental testing. Only for beam F was good conformity obtained of relationship *"F"* both for elastic as well as for elasto-plastic working of wood.

In elastic scope of analysis conducted, good conformity of equilibrium paths with laboratory results was obtained. Hill's criterion of anisotropic plasticity is not a perfect criterion for wood. Further works are indispensable on appropriate strength hypothesis which would well describe the working of bent timber elements.

7. Summing up

Testing was conducted on models in technical scale. "Reinforcement" in the form of CFRP strip was placed inside the section which constitutes the originality of the testing and simultaneously makes this solution useful in structural conservation of historical timber structures.

Results of the tests conducted clearly indicate the low level of utilizing the reinforcing insert (CFRP strip) placed inside the section in vertical system - the results of stresses in the strip in beams B2 and F1 are presented in Figs. 7 and 9. Section of the strip gets utilized to substantially greater extent, after destruction of wood, with no growth of force. The most appropriate solution seems to be preliminary compression of the strips which enables considerable utilization of their load capacity and what follows, on increasing the efficiency of reinforcement. Such a solution is however in fact not possible while reinforcing historical ceiling beams.

Performance of computer analyses utilizing FEM of elements of timber structures, enables more precise study of distribution of stresses inside the sections examined. It should however be remembered that utilization of FEM for elements of solid wood is burdened with considerable simplifications resulting from natural structure of wood as well as random, difficult to envisage, distribution of wood defects, specially knots and grain slopes.

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