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EXPERIMENTAL INVESTIGATION OF SCARF JOINT OF ‘LIGHTNING SIGN’ IN BENDING

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Abstract. *The paper presents a description and results of the research concerning one of the scarf joints, so-called ‘lightning sign’ (also described as ‘Bolt of lightning’ or ‘Trait-de-Jupiter’). This joint has been used and can be commonly found in wooden historical structures and is considered to be an interesting example of carpentry longitudinal joints. In the experimental part timber beams with this type of joint shaped in the different planes, horizontal and vertical, reinforced with spindle fasteners (metal bolts), were subjected to four-point bending tests. As a result, the static equilibrium paths and the bending capacities of individual beams were obtained. They were compared to the load-bearing capacity of the continuous reference beam. Moreover, a simplified numerical analysis based on FEM was carried out for comparison the rigidity of individual beams. A comparison of the results for series of beams is discussed and some conclusions and possible directions of the future actions in the subject are presented.*

1 INTRODUCTION

For centuries, wood has been a commonly used building material for different types of buildings: simple houses, residential buildings, sacral architecture, defensive structures, and sophisticated engineered structures like bridges, etc. Some of the timber structures have survived since that time and nowadays require interventions to maintain or improve their technical condition. One of the most important factors in this work is the issue of joints, which enable building elements to be connected into a single whole and for loading to be transferred between elements. Sometimes carpentry joints, that can be found in historical buildings, had sophisticated forms, which indicates the highly developed techniques and craftsmanship of builders of that time [1].

There are many types of carpentry joints in historical buildings distinguished by researchers, depending, for example, on their function and form (i.a. in [2]). One group includes scarf joints and splice joints. They were used to create a connection along the length of the two elements, when the available material could not cover the whole beam length. It was preferably to perform them in the least stressed sections, as the connecting elements at the point of contact could not bear a load greater than that in continuous sections [3]. They were applied to extend foundation beams and capping beams in building frames of historical structures as well as roof frame elements, such as purlins or rafter beams. Until the development of glue-laminated wood techniques, this was a commonly used method for extending wood elements [4]. Nowadays, scarf and splice carpentry joints are used i.a. to restore historical joints or to replenish the material in historical elements. Some examples of scarf and splice joints found in historical structures, from simple to refined forms, are presented in Figure 1.

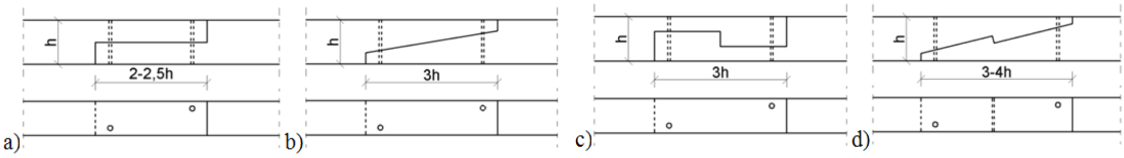


Figure 1: Different forms of scarf and splice joints: a) splice joint, b) nibbed scarf joint, c) tabled splice joint, d) stop-splayed scarf joint (‘Bolt of lightning’)

Scarf joints of lightning sing or stop-splayed scarf joints, also described as ‘Bolts of lightning’ or ‘Trait-de-Jupiter’ were presented i.a. in [5-8]. They are sophisticated forms of connections along the length of elements. Other examples of these forms are built-up beams or composite beams with a teethed joint – elements connected along their whole length with the scarf joints of the lightning sign, described i.a. in [9-11]. These types of joints are common for historical buildings. They have been used since ancient times (e.g., Roman bridge constructions). A great development of these forms was the time of the Italian Renaissance (e.g., Leon Battista Alberti – Figure 2a [12] or Leonardo da Vinci – Figure 2b [9]). Typically, the joints were wedged, which ensured a tight fitting joint and helped in load transferring.

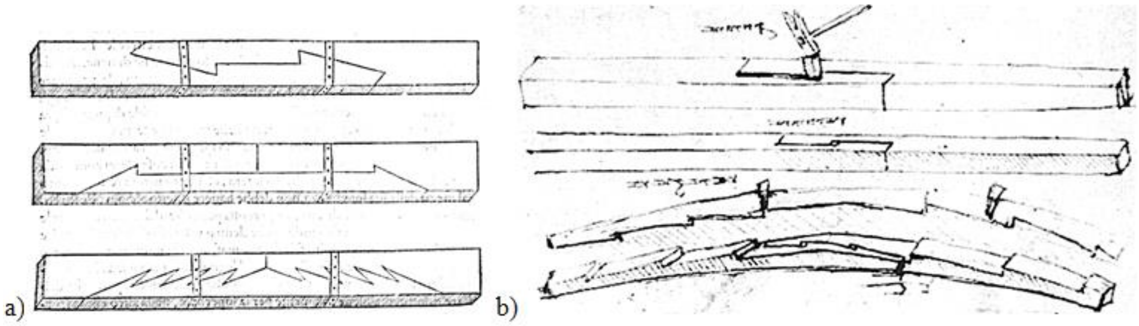


Figure 2: Drawings of scarf and splice carpentry joints according to a) L.B. Alberti [12], b) L. da Vinci [9]

A few available descriptions of research concerning typical scarf joints of lightning sign are presented, among others, in the following: [9-11,13-15]. Nevertheless, it has been observed that most of the research concerning the static behaviour of carpentry joints presented in the literature focused mainly on tenon joints and notched joints. There is definitely less research on joints subjected to bending loads as well as bending and tension or bending and compression. What is more, the vast majority of researchers, who have been dealing with this topic (among others, Rug et al. in [10,11], Hirst et al. in [14], and Fajman et al. in [16-21] as well as Kunecky et al. in [22-28]) claim that there is still a shortage of research for a full description of static behaviour of such joints and hence designing the most beneficial methods for repairing or strengthening them. Therefore, as a part of a research project (financed by Polish National Science Centre), some tests on the static behaviour of scarf joints of lightning sign subjected to bending and a simplified numerical analysis were carried out.

2 MATERIALS AND METHODS

2.1 Models for experimental tests

For the part of the experimental testing, beam models in technical scale from pine wood (*Pinus sylvestris L.*) of the minimum C24 class were prepared. The dimensions were 360 cm length and a cross-section measuring 12 cm x 18 cm. Testing involved 3 series with 3 beam models each. Series A included continuous beams as references. Other series included beams with scarf joints of lightning sign (stop-splayed scarf joints) created in the horizontal (series E) and vertical (series H) planes. The geometry of the joints was based on data obtained from real structures and the literature. Joints were strengthened with metal bolts (M12) and double-sided tooth plate connectors type C10 (Geka). The drawings of views, sections, and axonometric schemes of the beam models with joints used for the tests are shown in Figures 3 and 4.

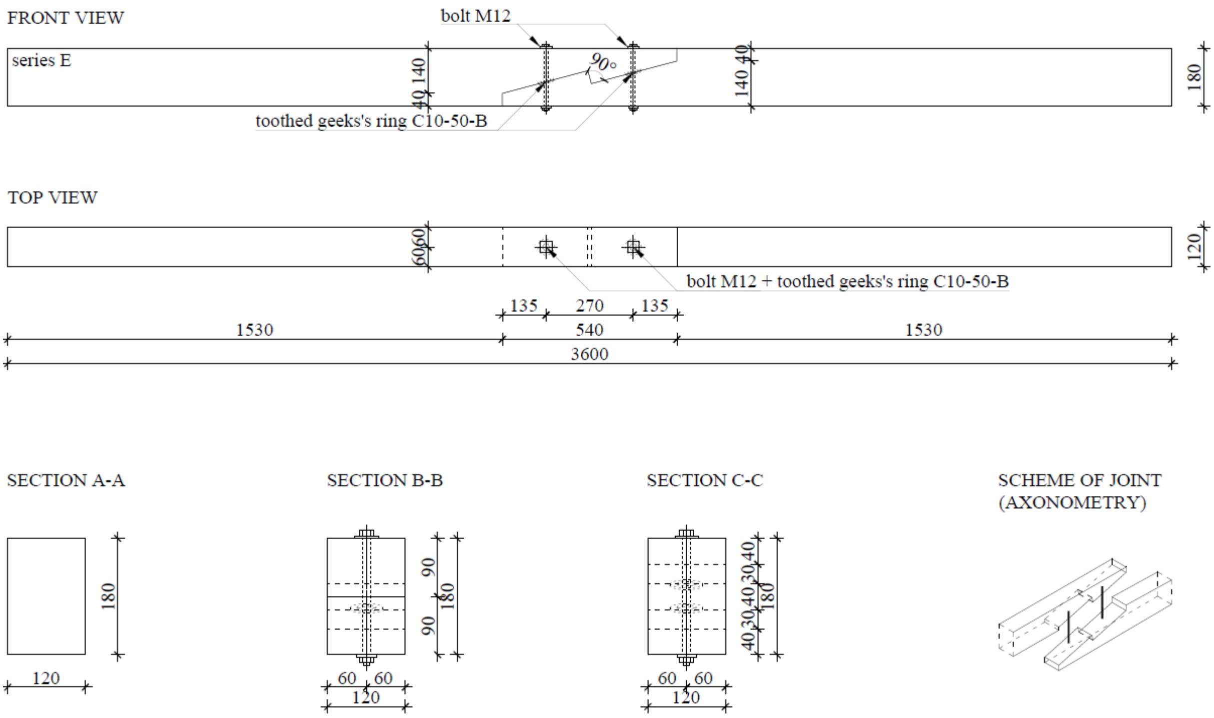


Figure 3: Beam model with scarf joint of lightning sign in the horizontal plane (series E)

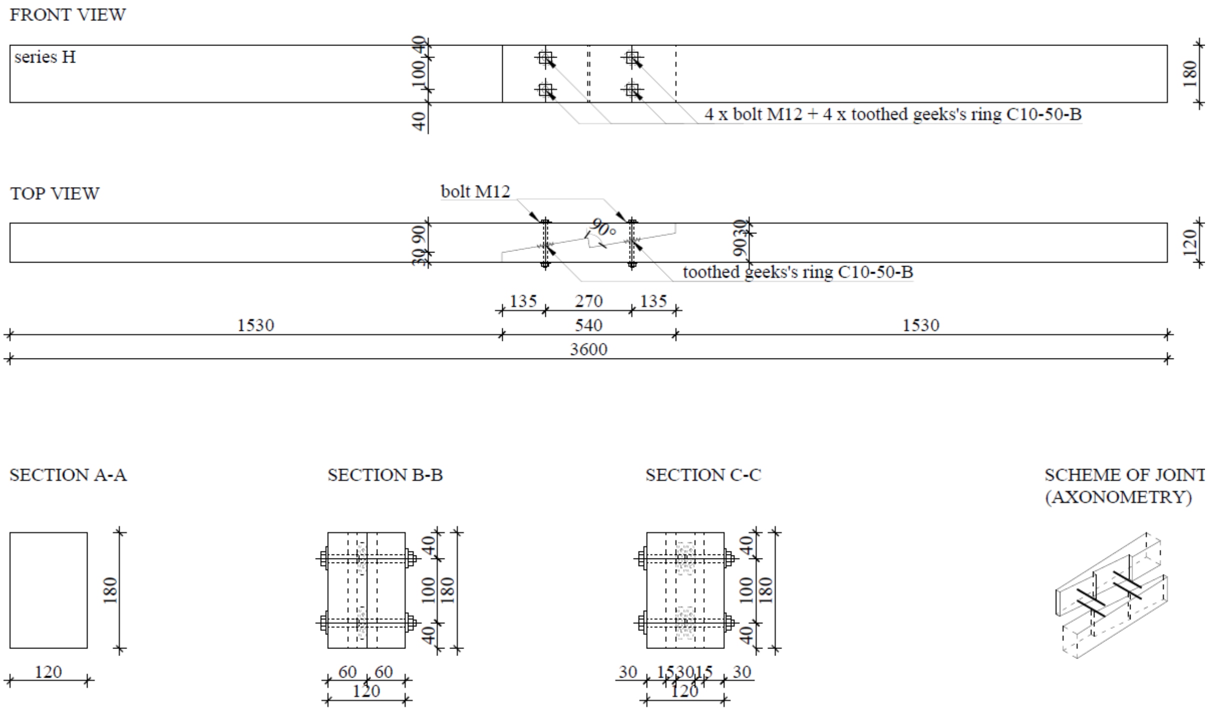
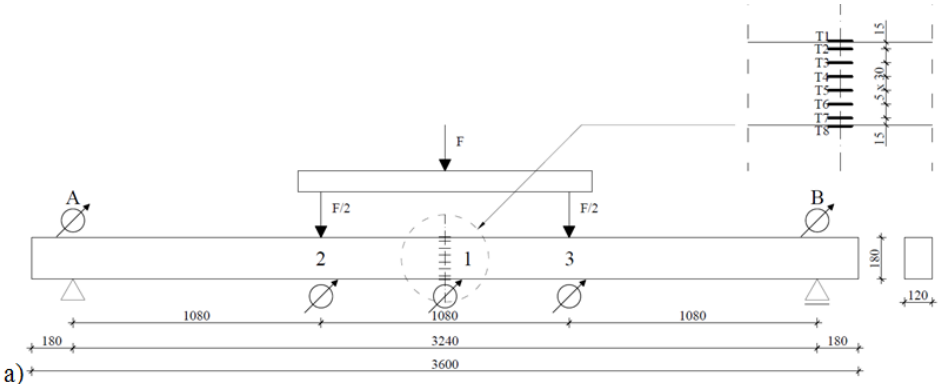


Figure 4: Beam model with scarf joint of lightning sign in the vertical plane (series H)

2.2 Experimental work – 4-point bending tests and material tests

The experimental testing was carried out at the Building Construction Laboratory of the Faculty of Civil Engineering at Wroclaw University of Science and Technology. To determine the load-bearing capacity and the static equilibrium paths (force – displacement paths), the beams were subjected to 4-point bending tests according to the standard procedure [29].

The beams were freely supported (with a fork support – no lateral buckling) at both ends. The span between the axes of the supports was 3.24 m. The beams were loaded symmetrically with a loading force applied at 2 points that allowed to obtain pure bending in the central part of the element. Load was applied with the speed of 5 mm/min. Registration of the deformations observed in the material was carried out by means of a series of strain gauges. A schematic model and view of the testing set are presented in Figure 5.



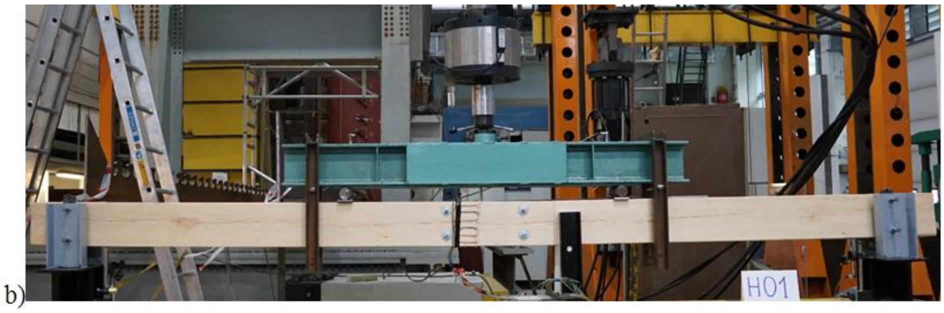


Figure 5: a) Schematic drawing of the testing set with the location of strain gauges, b) view of the testing set

Additionally, during the tests, the wood moisture content was determined using a resistance hygrometer (FMW moisture meter) in several locations on each tested beam. The moisture content of the elements was kept close to the required standard of 12% [29].

Moreover, based on the obtained force – displacement paths, the value of modulus of elasticity in bending was estimated according to the standard procedure [30]. Regression trend lines of three equilibrium paths of the tested reference beams (series A) for the load range from 0.1 F_{max} to 0.4 F_{max} were applied. The coefficient of correlation of these range lines was at least 0.998.

2.3 Finite element analysis

A simplified FEM numerical analysis was performed using ANSYS Workbench 16.0 computational programme. Wood was modelled as an elastic orthotropic material. The modulus of elasticity parallel to the grain on the basis of calculation was assumed to be 9800 MPa. Values of other material parameters needed for analysis: moduli Ey, Ez, Gxy, Gxz, Gyz and Poisson's ratios νxy, νxz, νyz (where x, y, z axes are axes respectively along the wood fibres, i.e. parallel to the grain and across the grain in the radial direction and across the grain in tangential directions, i.e. perpendicular to the grain) were estimated on the basis of relation from the literature [31,32]. Formulas and values of the material parameters used for FEM numerical analysis are presented in Table 1. The boundary conditions corresponded to the tests in the laboratory (load and support of the beam). The numerical model of the reference beam consisted of approx. 23000 hexahedral quad/tri elements (approx. 90000 nodes) with a size of 0.02 m (in the part of the beam outside the joint) and 0.01 m (in the area of the joint). An example is shown in Figure 6. Contact between the surfaces of individual elements was added as a standard contact with friction (with friction coefficients as follows: wood - wood μ = 0.2 and wood - steel μ = 0.5). The model was verified and then analysis was performed.

Table 1: Values of the material parameters used for FEM numerical analysis

E_x	$E_y = E_x/20$	$E_z = E_x/20$
9800 MPa	490 MPa	490 MPa
$G_{xy} = E_x/14$	**$G_{xz} = E_x/14$**	**$G_{yz} = G_{xy}/10$**
700 MPa	700 MPa	70 MPa
ν_{xy}	**ν_{xz}**	**ν_{yz}**
0.37	0.42	0.47

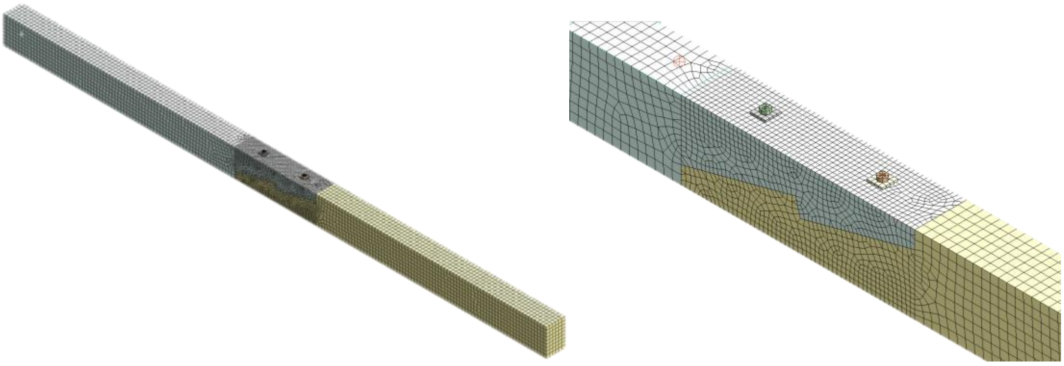


Figure 6: FEM numerical model of an example beam

3 RESULTS AND DISCUSSION

3.1 Experimental work and FEM analysis results

In the experimental testing, the beam models were loaded up to the failure. Ultimate force values were noted, load-bearing capacities for bending for each series were calculated. Deflections (displacements) in the middle span of the beam were measured by test equipment and estimated by numerical analysis. The results of experimental testing for all series of beams are presented in Table 2.

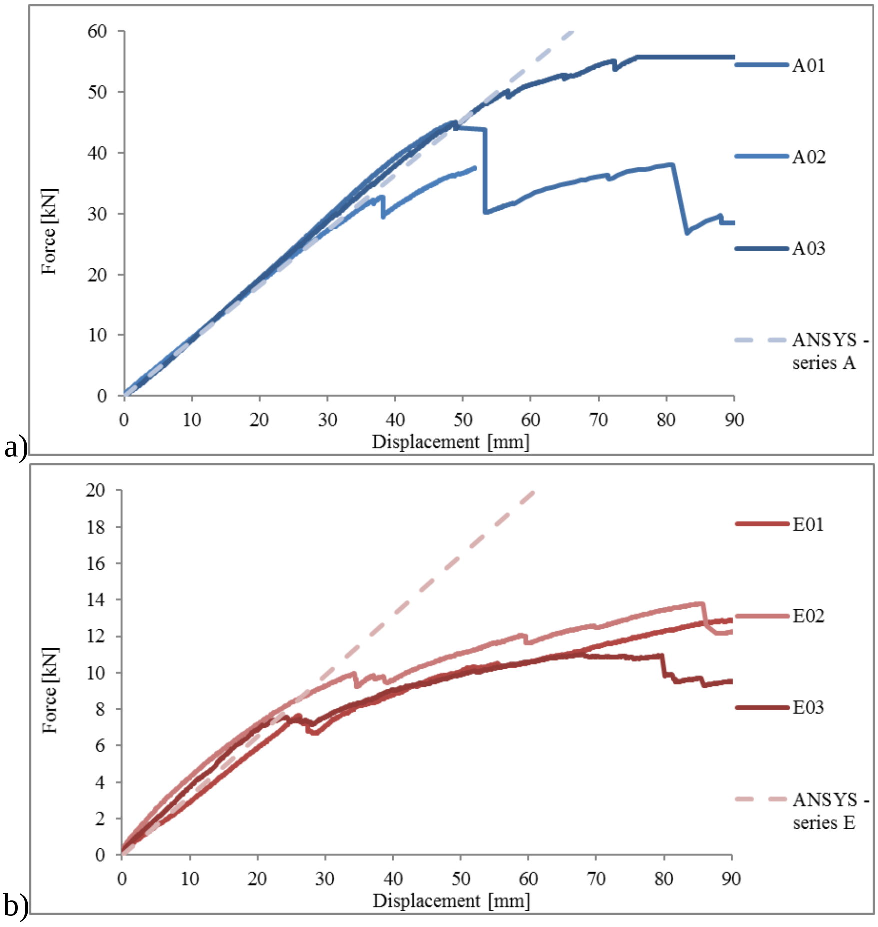
Table 2: Presentation of results for the tested beams

	Reference beam (series A)	Beam with joint in the horizontal plane (series E)	Beam with joint in the vertical plane (series H)
Ultimate force values [kN]	44.95	13.21	16.16
	37.52	13.79	16.91
	55.74	11.00	16.03
Mean ultimate force value [kN]	**46.07**	**12.67**	**16.37**
Mean load-bearing capacity for bending [kNm]	24.88	6.84	8.84
Mean deflection in the middle span by 10 kN from tests/ numerical analysis [mm]	12.40/ 11.00	37.50/ 30.50	15.00/ 17.00
Mean deflection in the middle of the span by maximum load [mm]	63.80	82.49	43.89

The failure of the tested beams for continuous beams (series A) resulted from shearing of fibers in the bottom part of the central area of the beam. For the beams with joints (series E and H), the failure involved a loosening of the joint in the lower zone of the central part of the beam and the appearance of cracks and fractures on the edges of the joint and in areas which had been weakened by metal fasteners or earlier material flaws, such as knots or primary cracks of the beam. The failure views of the selected models are presented in Figure 7.

Figure 7: Views of the failure of exemplary beams with joints: a) beam E02, b) beam H03

The equilibrium paths for each beam obtained from the tests and from FEM numerical analysis are presented in Figure 8. Material deformations registered by the strain gauges set for the selected beams are shown in Figure 9. For the continuous beam, it is a typical image of material strain in bending, whereas for the beam in series E it is a typical curve shape for the composite cross-section in bending (see, i.a. in [10]).



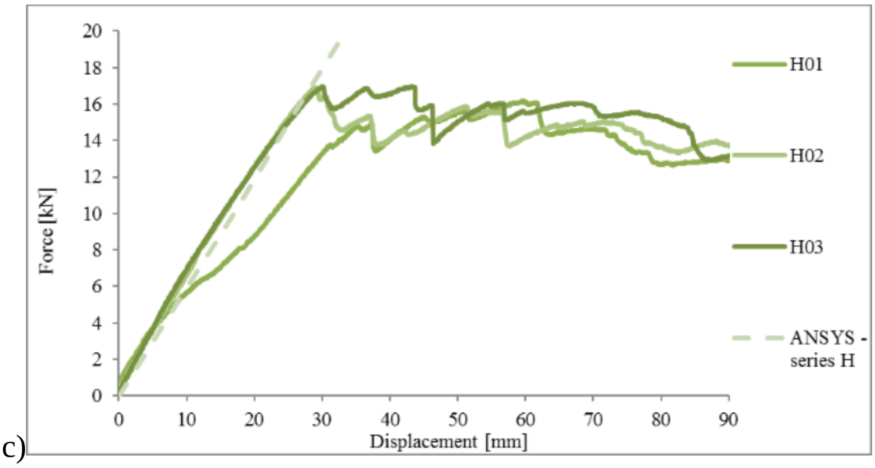


Figure 8: Force – displacement paths for beams a) continuous (series A), b) with scarf joint of lightning sign in the horizontal plane (series E), c) with scarf joint of lightning sign in the vertical plane (series H)

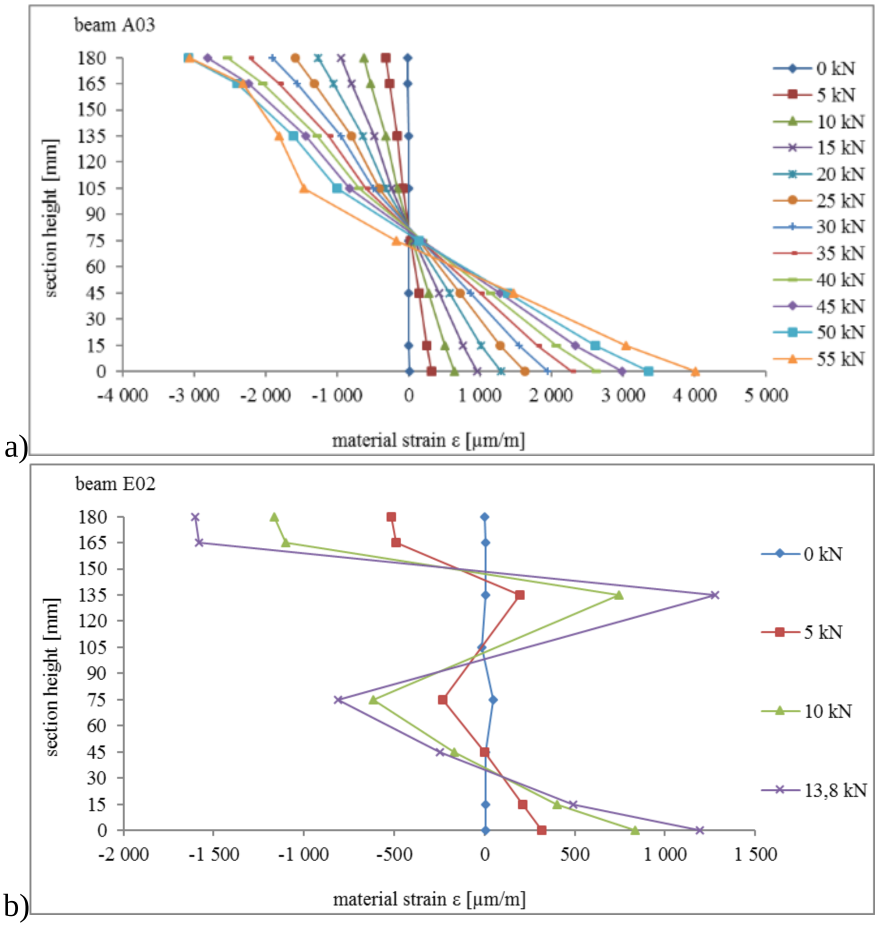


Figure 9: Deformation of material in the central cross-section for selected beams: a) continuous (beam A03), b) with scarf joint of lightning sign in the horizontal plane (beam E02)

3.2 Comparison of results and discussion

The mean load bearing capacity in bending for continuous beams (series A) is 24.88 kNm, whereas beams with joints present capacities of 6.48 kNm (series E) and 8.84 kNm (series H), which constitutes respectively 27.5% and 35.5% of load-bearing capacity of reference beam. Beams with scarf joints in the vertical plane (series H) have higher values of load bearing capacity in comparison with beams with scarf joints in the horizontal plane (series E).

Regarding the stiffness of the tested beams, defined as the ratio of loading force to deflection (displacement), estimated on the basis of force – displacement paths, the highest value is noticed for the continuous beams (series A), what is an expected result. Based on the tests and numerical analysis, it was observed that beams with scarf joints have lower stiffness in relation to the continuous beams. When comparing beams with scarf joints to each other, it must be said that beams with joints in the vertical plane (series H) have higher stiffness than beams with joints in the horizontal plane (series E).

Comparison of static equilibrium paths from the tests and numerical analysis are shown in Figure 10. Comparison of load-bearing capacity and stiffness for jointed beams and reference beam is presented in Table 3.

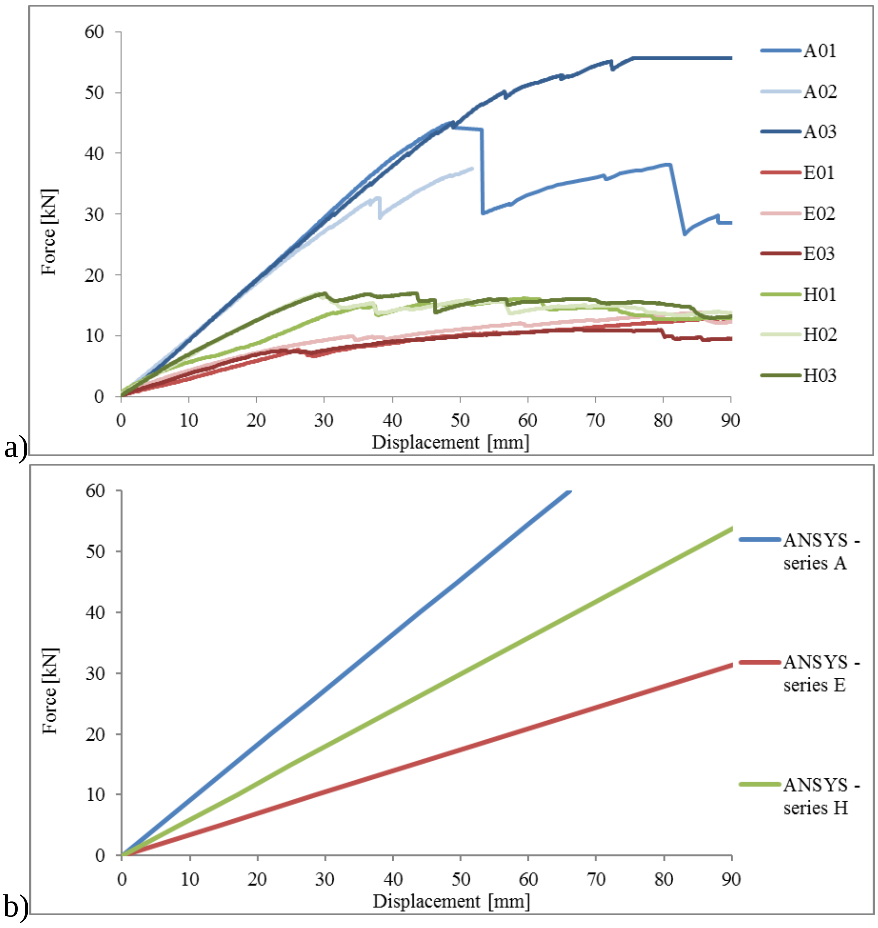


Figure 10: Force – displacement paths for tested beams a) from experimental tests, b) from numerical analysis

Table 3: Experimental tests results comparison

	Reference beam (series A)	Beam with joint in the horizontal plane (series E)	Beam with joint in the vertical plane (series H)
Ratio of load-bearing capacity in comparison to reference beam	100%	27.5%	35.5%
Ratio of stiffness in comparison to reference beam from tests/ numerical analysis	100%	33.0%/ 36.0%	83.0%/ 65.0%

4 CONCLUSIONS

What should be highlighted is the fact that the laboratory testing involved only three beam models in each series, what resulted in quite high variations of results. It can be concluded that it is due to some primary material flaws. Wood itself is a natural material and therefore it can be characterized by large variation, which is related to some initial cracks, knots, etc.

Experimental tests carried out in the laboratory on technical-scale models and simplified numerical analysis present the static behavior of the described joints under bending load in comparison to the behavior of a continuous reference beam. Regardless of the joint plane, horizontal or vertical, the failure modes of the beams were similar (loosening of the joint in the lower central zone and appearance of cracks and fractures near the edges or fasteners). The levels of load-bearing capacity in bending obtained in laboratory experimental tests for beams with joints compared to the reference beam amounted up to one-third (27.5% for joints created in the horizontal plane and 35.5% for joints created in the vertical plane). The stiffness levels obtained in the tests and numerical analysis amounted from one-third up to two-thirds or even more (33.0%/ 36.0% for joints created in the horizontal plane and 83.0%/ 65.0% for joints created in the vertical plane) in comparison to the reference beam. Beams with joints in the horizontal plane (series E) obtained significantly lower levels of load-bearing capacity and stiffness in comparison with beams with joints in the vertical plane (series H). This may indicate that the creation of scarf joints of lightning sign in the vertical plane is a more favorable solution.

The carried out research and analysis delivered a description of the static behavior of scarf joints subjected to bending. For more precise information, further laboratory tests and more detailed and accurate numerical analysis are recommended.

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