Anna Arciszewska-Kędzior*, Jiří Kunecký**, Hana Hasníková***

Mechanical response of a lap scarf joint with inclined faces and wooden dowels under combined loading

Reakcja mechaniczna połączenia na zakładkę z zamkiem ukośnym i drewnianymi kołkami w warunkach obciążenia złożonego

Key words: lap scarf joint, combined loading, FEM

Słowa kluczowe: połączenie na zakładkę z zamkiem, obciążenie złożone, MES

1. INTRODUCTION

A lap scarf joint with inclined contact faces and wooden dowels is a commonly used connection for repairing damaged beams in historical structures in the Czech Republic and is a focus of this study. The damage occurs commonly at the ends of a beam due to contact with other materials such as masonry walls. In the bearing areas a beam would undergo moisture damage or would suffer from fungi attacks. In the historical roofs it is important to maintain the original materials as much as possible therefore a damaged beam should be provided prosthesis rather than being replaced with a new beam. The lap scarf joint is used to connect a new prosthesis, which is provided to replace the damaged part of the original beam, with the remaining undamaged part of the beam. The main idea of this type of connection is to provide an aesthetically pleasing repair that would allow maintaining the load capacity of the original beam and would not affect the historical authenticity of the structure. In the trussed roofs, as oppose to the simple flat roofs framed with beams and joists, the timber beams carry combined loads. Therefore, it was desired to simulate the real loading conditions found in historical timber trusses such as combined compression and bending for the rafters and struts or tension and bending for the tie beams and braces. Furthermore, it is known that in some historical structures with floor construction made of wood beams the beams may carry tensile loads due to repairs made for the stone or masonry walls. The walls that are incapable of carrying bending moment have the metal stripes or ties anchored at the level of the floor beams that tie the wall and the floor together and create the tensile forces in the wood beams. Therefore, the lap scarf joint used for repairing these beams should be tested to carry combined tension and bending assuming that tension is not a controlling load. Knowing that experimental setup and testing of joints under combined loads is difficult and time consuming, the beams with joints were also tested under pure bending to provide the reference values that can be used for common analysis of the joints. It was desired to conclude if the combined load application is in fact highly influential on the mechanical performance of the lap scarf joints with inclined faces and wooden dowels. Timber joints in Europe are designed according to European standards

* MSc., Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, v.v.i.
** Ing. PhD., Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, v.v.i.
*** Ing., Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, v.v.i.

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such as Eurocode 5 (EC5, [1]) where principles for designing dowel connections are based on Johansen's yield theory [2]. However, the European Yield Model considers scenarios only for the ductile failure. Many researchers expressed their concern to introduce the brittle splitting failure criterion for timber connections into design codes or expand the existing criteria that are not as precise as the EYM for the ductile failures [4] [5] [6]. Therefore, the historical timber joints are commonly approached by experimental and FE research techniques. This combination of techniques was used already to analyze behavior of the lap scarf joints with dowels by Arciszewska-Kędzior et al. [7] who proved that numerical models in combination with some EC5 equations for brittle failure of doweled connections may closely predict the stiffness and strength of the beams with theses specific joints. Another paper regarding the lapped joints presented in the paper was written by Kunecký et al. [8].

2. MATERIALS AND METHODS

This research consisted of two steps: (i) experimental testing of timber beams with lap scarf joint with wooden dowels in bending and under combined loads, and (ii) virtual testing of the joints using finite element analysis (FEA).

2.1. Experimental Tests

The purpose of the experimental testing was to analyze yield load and stiffness of timber beams with lap scarf joints connected by wooden dowels under different loading arrangements. It was also desired to compare these results with the outcomes from testing the reference beams. Moreover, experimental data could be used for validation of numerical models. There were three types of tests performed: pure bending test, combined compression and bending test, and combined tension and bending.

Experimental data was collected for the four-dowel-joints with the contact faces inclined to 60 and 45 degrees. Also, there were the specimens with the two-face joints and the three-face joints (Fig. 1). Testing was performed on small scale specimens made of Norway spruce timber that were 50 mm × 60 mm in cross-section and the final beam-span was 1.5 m. The wooden dowels were 6 mm in diameter and were made of European beech wood. The detailed dimensions of the samples and the test set-up are shown in Fig. 1 and Fig. 2. During all tests the displacements at mid-span were measured. The force applied to a beam was recorded from the pressure of hydraulic inducers GTM series K (max. force 50 kN) that were used for loading the specimen. The loading rate was 10 mm/min. All tests were carried out until failure occurred; hence the ultimate strength was also obtained. Absolute moisture content was measured for each beam and the mean value was 12%.

2.1.1. Bending Test

The first test type was the three point bending test for which the beam was simply supported at each end and the point load was applied at the center of the beam-span. This test was performed on the joints with oblique contact faces inclined to 45 degrees (b45-x). In addition, the continuous beams without joints were tested to provide the reference data (ref).

2.1.2. Combined Compression and Bending Test (C/B)

The second test type was the combined compression and bending test. The beam was inclined to 45 degree and the point load was applied as far from the

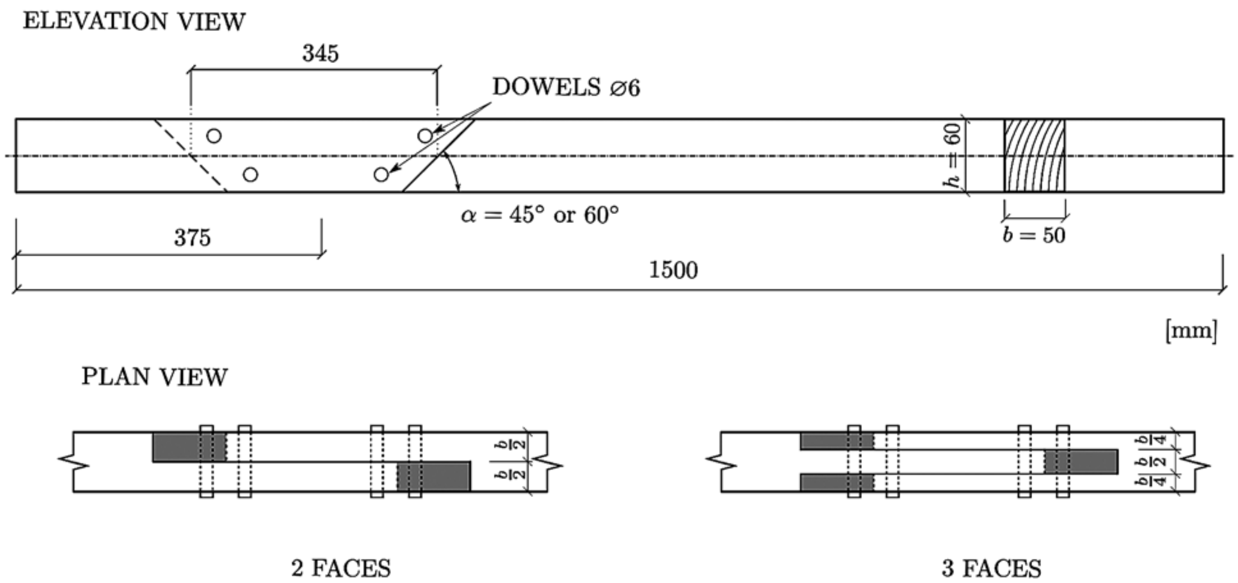


Fig. 1. Specimens' dimensions

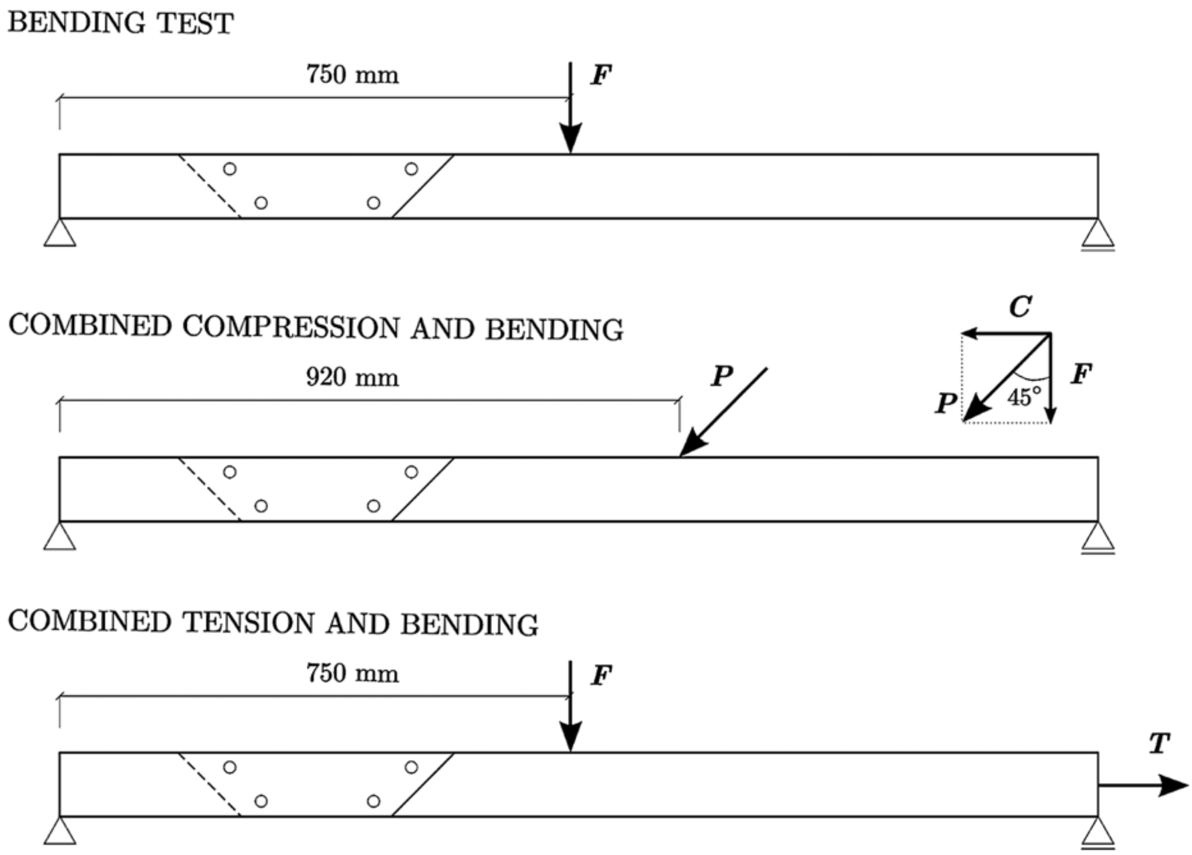


Fig. 2. Experimental set up

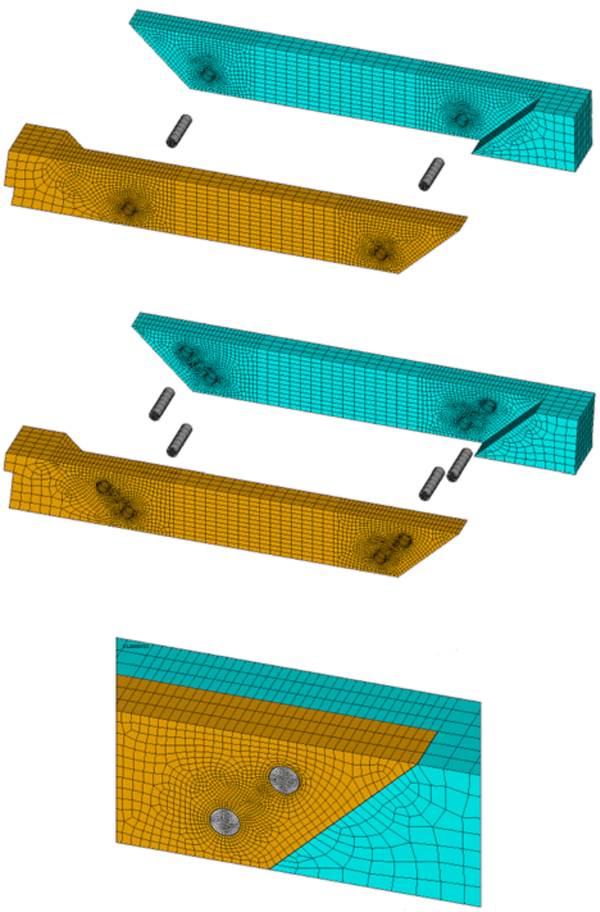


Fig. 3. Finite element model: elements of the joint (top), detail (bottom)

joint as the laboratory set up allowed to ensure that the magnitude of the resulting axial compression will influence joint's behavior. The joints with 45 (cb45-x) and 60 (cb60-x) degree contact faces were tested.

2.1.3. Combined Tension and Bending Test (T/B)

The third test type was designed for combined tension and bending. The beam was tested in the same arrangement as for the pure bending test with additional tensile force of 1200 N applied at one end of the beam (Fig. 2). The joints with 45 (tb45-x) and 60 (tb60-x) degree contact faces were tested.

2.2. FEA

Finite Element Analysis (FEA) was performed to create a functional numerical model of the lap scarf joint with dowels that would allow exploring variations of the joints geometries and parameters. First phase of FEA consisted of modeling the joints that were tested in the laboratory (Fig. 3).

All finite element models were created in ANSYS v. 14.5 using SOLID95 element type. Boundary conditions reflected physical tests, i.e. the supports were placed in the ends of the beam and the forces were applied in accordance with each experiment type. The numerical model used the hexahedral quadratic elements. A denser mesh was used for meshing dowels and areas of contact, i.e. near the holes and oblique faces. Contact between the joint faces and between the holes

Table 1. Material model for beams (Norway Spruce) and dowels (English Oak) used in FEA

Wood	MOE_T	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	υ_{LR}	υ_{LT}	υ_{RT}
	MPa	MPa			MPa			MPa		
Norway Spruce	7940	15424*	892*	326*	647*	535*	60*	0.014	0.557	0.023
English Oak	13066	11778	1028	2046	1100	234	1041	0.064	0.37	0.033

* modified with factor $k = 9300/8210$

in the joint and the dowels was defined as a standard contact using 3D surface-to-surface contact elements CONTA174 and target elements TARGE170. Contact algorithm was defined as Augmented Lagrangian with contact stiffness updated at each iteration. Gauss integration points were used for locating the contact points. Two types of wood materials were defined in each FE model: (a) material of beam made of Norway spruce, and (b) material of dowel for which English oak was assigned (Table 1). Both wooden materials were modeled as linear elastic orthotropic materials. The dowels were modeled with English oak properties as the properties of English beech are very similar nevertheless hard to be found in the literature. Also, in this scale the properties of these two kind of woods are not distinguishable. As for the beam material, MOE of Norway Spruce used in this research was tested in static bending prior to testing the jointed beams and resulted in the mean MOE of 9300 MPa. Experimentally defined MOE was compared with the available literature [3] for Norway Spruce from the same geographical region which used a value 8210 MPa for bending MOE. Comparison showed that timber used in this study is slightly less stiff. Therefore, the factor *k* = *9300/8210*, a ratio of mean experimental MOE measured in the laboratory to the mean MOE derived by Požgaj [3], was defined and used as a conversion factor for E and G parameters for Norway Spruce only. Mechanical parameters for English Oak are according to [3] as there was no experimental testing performed.

3. RESULTS AND DISCUSSION

Prior to experimental work the material testing was performed. It was desired to compare the properties of the beams for all groups of joints to ensure that the properties of materials do not influence the final mechanical properties. Also, the properties of materials were needed for the numerical models. For Norway Spruce the resulting mean MOE from bending tests was 9300 MPa and the mean density of this timber was 500 kg/m^3.

3.1. Experimental results

First, a failure pattern that is a reliable source of information about joints' behavior was analyzed. For each test a failure pattern was recorded and investigated. There were three common failure modes observed: (a) tensile failure perpendicular to grains occurred in a beam near dowels or propagating from the inclined face; (b) flexural failure occurring near the lap's limited cross-section at the bottom of beam, and (c) shear failure of wooden dowels (Fig. 4). It is important to note

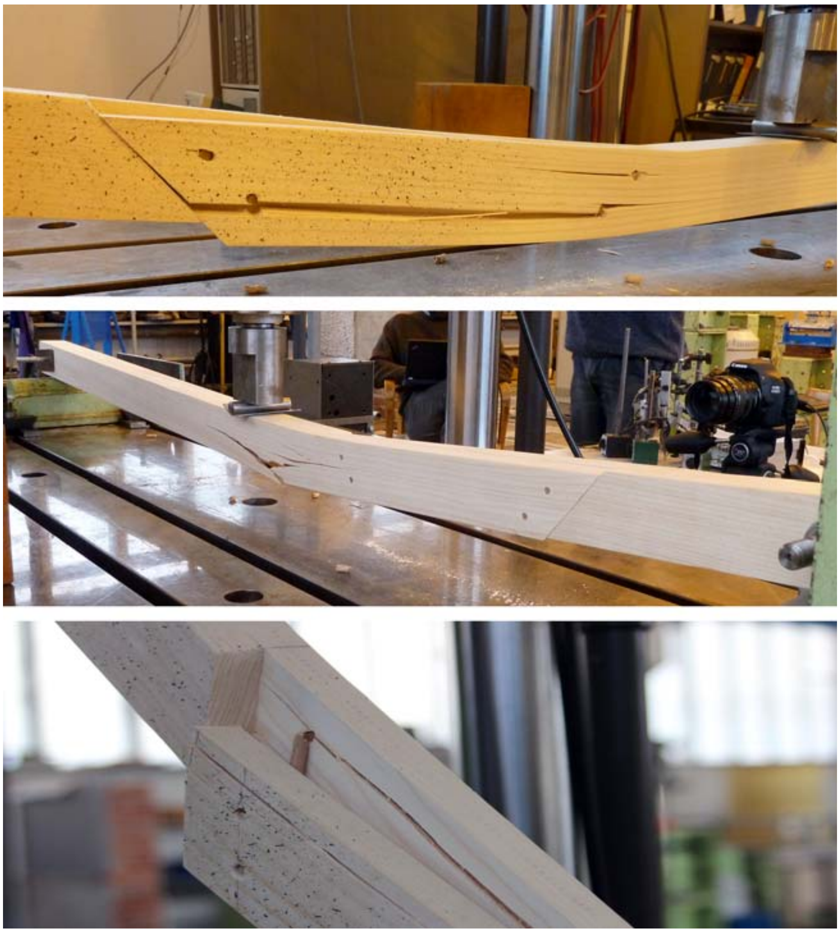
(a)
(b)
(c)


Fig. 4. Common failure patterns (a), (b), and (c)

Table 2. Experimental and numerical results

Exp. Type	No. of exp.	Experiments						FEM		Exp-FEM Error	
		k_lin	stdev_k	F_max	stdev_F	N (T^+; C^-)	$M_{max@joint}$	k_lin	F_max	Err_k	Err_F
		N/mm	–	kN	–	kN	kNmm	N/mm	kN	%	%
b45	4	122.4	15.6	3.4	0.1	0	602	135.0	3.2	9.3	-5.9
tb45	4	103.0	13.8	3.1	0.4	1.2	542	127.0	2.7	18.9	-14.8
cb45	4	122.4	37.0	3.1	0.8	-3.1	420	157.0	7.4	22.0	58.0
tb60	4	95.0	8.3	2.6	0.4	1.2	455	126.0	N/A	24.6	N/A
cb60	4	160.7	60.8	3.9	0.4	-3.9	550	159.0	5.4	-1.1	27.8
3f-b45	4	134.2	10.0	4.1	0.2	0	713	144.0	3.8	6.8	-7.2
3f-tb45	4	104.9	6.6	3.4	0.3	1.2	590	136.0	3.4	22.8	0.7
ref	10	162.7	33.3	6.2	1.5	0	N/A	160.0	N/A	-1.7	N/A

that mode (c) was observed in all T/B experiments for the joints with the 60 degree faces and only in one T/B experiment for joints with 45 degree faces. Among all the other experiments the mode (a) was the most common failure pattern.

Experimental testing was used to analyze mechanical behavior of the jointed beams. The behavior is best illustrated using force-displacement graphs (Fig. 5). It is common that after the initial linear behavior the jointed beams fail in a sudden and brittle manner. The linear stiffness 'k_lin' and the ultimate loads 'F_max' were recorded and tabled (Table 2). Results for different loading arrangements were compared for beams with the 60-degree joints and the 45-degree joints.

The beams with 60-degree joints were tested only in combined loads arrangements T/B and C/B. The pure bending test was not performed because it is assumed that the 45-degree joints are more efficient in carrying bending moment. Experimental tests show that applying combined T/B results in significantly lower stiffness 'k_lin' and load carrying capacity 'F_max' in comparison to the beams subjected to combined C/B (Table 2). The common failure mode (c) for the T/B tests indicates that tensile force subjected to a beam changes its failure pattern. Tension highly influences the load accumulation in the dowels that finally fail in shear. On the contrary, in C/B tests the failure pattern is (a) (Fig. 4) and it is as for bending tests for 45-degree joints. It is recognized that the behavior of the beams in the combined C/B testing is controlled by bending.

For the 45-degree joints the three types of tests were performed: the three-point bending test, combined T/B test, and combined C/B test. It was seen that the beams subjected to T/B result in lower stiffness and slightly lower carrying capacity than the beams under pure bending. On the contrary, the C/B tests show that applying compression to a jointed beam subjected to bending has a positive influence on the stiffness while carrying capacity of the beams slightly decreases if compared to pure bending tests. Nevertheless, the results of the C/B tests for the 45 degree joints are much lower than for the 60 degree joints. Therefore, it may be recommended to use the 60 degree joints for the rafter prostheses that carry both compression and bending loads. For the 60 degree joints the compression forces help interlocking of the joint's faces which improves the mechanical performance of the whole beam.

Furthermore, the T/B tests for 45 and 60 degree joints again show that the angle of the contact face influences joint's performance. The beams with the joints with 45 degree face show higher results because with the lower angle the bending force has a larger impact on the joint's behavior. It may be assumed that for the joints with 60 degree faces the tensile load controls the failure. Finally, it may be said that the tensile forces highly impact the mechanical behavior of the lap scarf joint with dowels; therefore joint's geometry has to be designed carefully and the strength of connectors is of high importance. As oppose to the conclusions from the C/B test, for the beams that carry combined tension and bending the lap scarf joint with 45 degree contact faces is more efficient in the means of stiffness and strength.

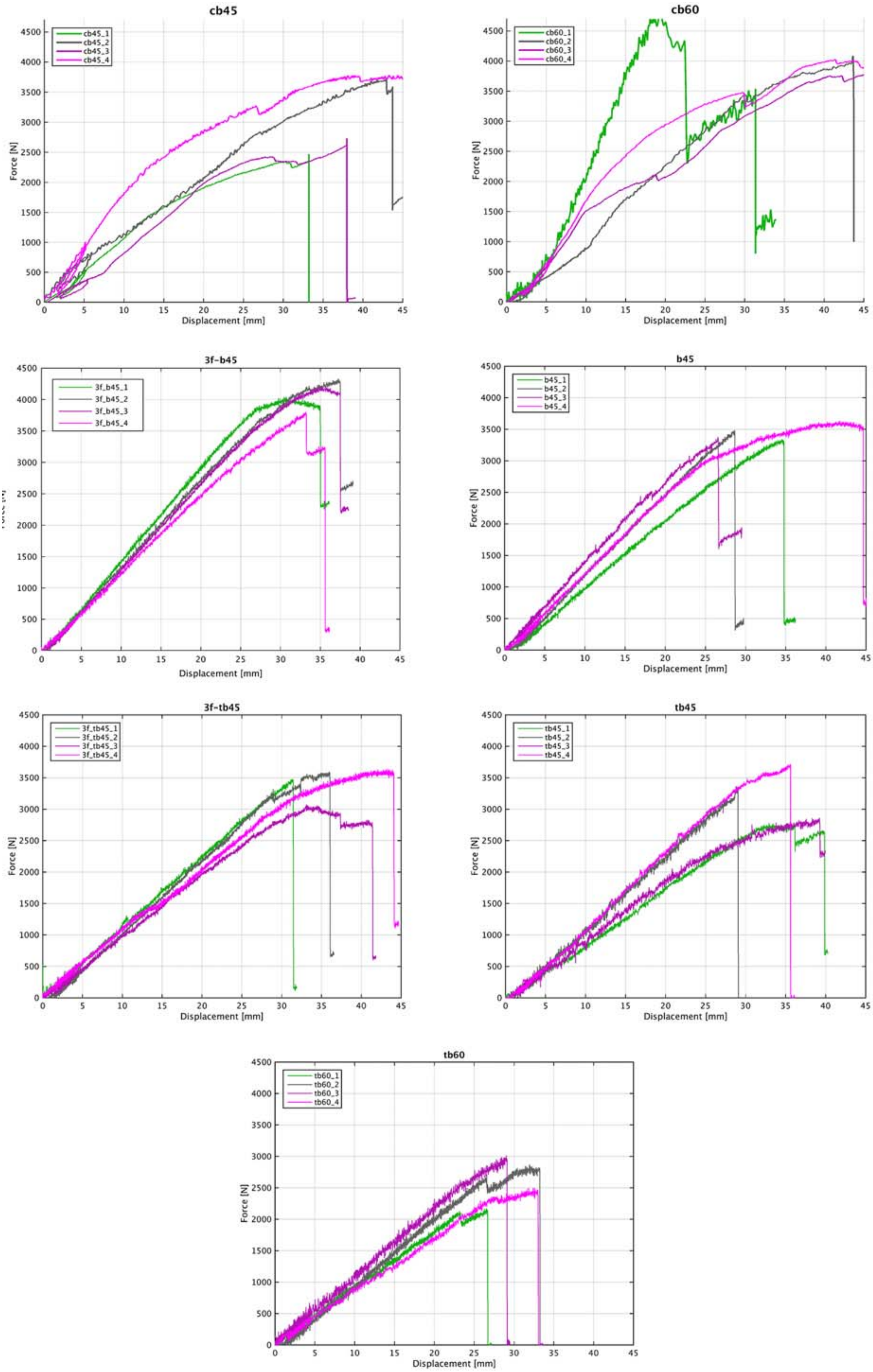


Fig. 5. Force-displacement graphs

Another comparison was made for the 45 degree joints with the two-face geometry and for the three-face geometry. Since it has been concluded that the 60 degree joints are more efficient for combined compression and bending the new three-face joints with 45 degree faces were tested only in pure bending and combined T/B. Similarly to other experiments, the results indicate that tensile forces introduced to a jointed beam subjected to bending negatively influence both the linear stiffness and carrying capacity of the beam. It is also seen that the beams with the three-face joints provide the highest linear stiffness and strength of beam among all specimens tested. These joints are also considered the most authentic historically since the most of the original material is intact. Also, the three-face joints are considered more aesthetic.

3.2. FEA RESULTS

Stiffness values computed using data obtained from FE models show that all beams, regardless the load arrangement, reach similar stiffness (Table 2). That confirms the findings from experimental work. Furthermore, the trend of the highest stiffness for C/B loading and the lowest for T/B loading is also observed in FEA. The model provides a low relative error for stiffness 'Err_k' (Table 2) therefore the FEM results can be considered credible and can be used for the failure estimation of the beams 'FEM F_max'. However, one issue regarding FE modeling of the C/B combined loading should be mentioned. The stiffness and the maximal force assessed by FE method in C/B are far higher from those observed in the experiments. This can be caused by the extensive friction influence of the FE model. However, to recognize such a friction coefficient, a lot of experiments has to be performed which can go out of focus of the article and can be a subject of a separate research.

Failure of the jointed beams in FEA is calculated using the force distribution around the dowels since the timber joint mostly failed in tension perpendicular to grains near dowels' holes. That approach was already taken and proven to fairly estimate the experimental results by Arciszewska-Kędzior et al. [7]. This approach focuses on analyzing the load distribution around the dowels in the joint and selecting the most loaded dowel to estimate the failure of the whole connection. Failure of timber connections is well described in many design codes when assuming that the ductile failure is observed. The European Yield Model (EYM) which is based on Johansen theory [2] and incorporated into Eurocode EC5 [1] is a very useful tool to estimate the failure loads for timber connections. However, the EYM considers scenarios only for the ductile failure. Many researchers expressed their concern to introduce the brittle splitting failure criterion for timber connections into design codes or expand the existing criteria that are not as precise as the EYM for the ductile failures [4], [5], [6]. The brittle failure rather than a ductile failure is the case analyzed in this research and therefore the EYM cannot be used to calculate failure loads for the examined joints. For the brittle splitting failure the EC5 introduces a very simple and generalized equation based on beams' dimensions and connectors' location. EC5 [1] proposes a following equation:

$$F_{90,Rk} = 14bw\sqrt{\frac{h_e}{(1-\frac{h_e}{h})}} \qquad (1)$$

Where, $F_{90,Rk}$ (N) is a splitting force perpendicular to grain, b (mm) is the width of the beam, h (mm) is the height of the beam, and h_e (mm) is the loaded edge distance. The factor '14' ($N/mm^{1.5}$) given in the equation is essentially based on timber properties. EC5 [1] recommends comparing the splitting failure force with the half of the load applied to the connection. Nevertheless, it has been proven experimentally by Jensen [4] that the splitting failure load should be compared with the total force applied to the connection. For the purpose of this research Jensen's approach is adopted [4].

For all the joints the loaded edge distance was taken as 18 mm since it was observed during experimental work that the bottom holes are prone to potential cracks. The splitting force perpendicular to grain $F_{90,Rk}$ resulted in 5020 N and was compared with the sum of forces around each dowel coming from numerical analysis. It was observed that the bottom dowel located toward the center of the beam is the most loaded location for each load arrangement. This dowel was used to estimate the final failure force for the numerical model FEM 'F_{max}' (Table 2). Results show that the model estimates very closely the linear stiffness and the load carrying capacities. Estimation was not made for the 60 degree joints in T/B tests since it was concluded from the experimental work that the failure mode is related to a shear failure of the dowels.

4. CONCLUSIONS

This study aimed to analyze mechanical behavior of the lap scarf joint with oblique contact faces and wooden dowels. The mechanism of the joint's performance under different load arrangements was recognized. Experimental tests and numerical models helped understanding loads distribution in the joints and recognize the key parameters influencing beam's behavior.

It was concluded from both experimental testing and numerical modeling that the beam with a joint with 45-degree faces under combined axial compression and bending can carry slightly lower loads and shows unchanged stiffness than the joint subjected to pure bending. Therefore, testing the joints in combined compression and bending to gather the mechanical parameters can be neglected as the pure bending is a good indicator of the joint's performance. Also, the test set-up for the pure bending testing is less difficult than for combined load testing. Nevertheless, combined C/B testing was useful to realize that the 60-degree joints perform better under combined C/B than the 45-degree joints which are assumed to be the most efficient under the pure bending loads. Therefore, it may be recommended to use the 60-degree joints for reparation of rafters in historical trusses.

Furthermore, the lap scarf joint under combined axial tension and bending shows the lowest stiffness and strength. Therefore, this load arrangement is the most critical for the joint's performance. Experimental results show, that the decrease in stiffness and carrying capacity obtained from the T/B tests is not significant, however, the failure pattern changes. It has been concluded that for the beams that carry combined tension and bending the joint with 45-degree faces is more efficient in both stiffness and strength. Experiments also show that failure of joints subjected to T/B depends on connectors' strength therefore it is important to carefully analyze the lap scarf joints that will be used for repairing beams that carry combined tension and bending loads.

Numerical models indicate that in all three load arrangements: pure bending, combined compression and bending, and combined tension and bending the bottom dowels are loaded more than the top dowels. Furthermore, it is the bottom dowel located toward the center of the beam that is loaded the most among all four dowels. Therefore, the failure is expected near this dowel and it has been confirmed by several failure patterns observed during the experiments. Furthermore, combination of FEA results and EC equation for brittle failure of connections loaded perpendicular to grains may be used to effectively estimate the stiffness and load carrying capacity of the beam with lap scarf joint with inclined faces and dowels. Nevertheless, in connections highly impacted by the tensile forces for which wooden dowels fail in shear the EYM should be used for strength calculations.

Lastly, it has been proven that a 45 degree joint with three contact faces is more efficient mechanically than the connection provided by a joint with two contact faces. Moreover, this type of joint is more aesthetic and since it allows maintaining more of the original material. Therefore, the authenticity of the repaired structure is not highly impacted. Nevertheless, the three-face joint is a more complicated and time demanding connection than the two-face joint for the manufacturers. Concluding, the three-face joint has to be used when a higher strength and stiffness are required. For the beams that will perform well with slightly reduced strength the two-face joint is suitable.

Lastly, it was calculated using experimental data that a jointed beam with a scarf joint with oblique contact faces and wooden dowels in the three-point bending test provides between 60% of the original beams' strength and the linear stiffness of beam is not influenced significantly.

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Abstract

The paper focuses on analyzing mechanical behavior of a lap scarf joint with inclined contact faces and wooden dowels which is a commonly used connection for repairing damaged beams in historical structures. Experimental and numerical analysis were performed to investigate mechanical parameters such as stiffness and strength of this type of prosthesis. This study concentrates on investigating joints behavior under combined loading, compression and bending, and tension and bending. It was desired to simulate the real loading conditions found in historical timber trusses such as combined compression and bending for rafters or tension and bending for tie beams. Experimental work has been designed for testing the jointed beams in small scale subjected to pure bending, combined compression and bending and combined tension and bending. Finally, a finite element model was constructed and validated using experimental output and further used for estimating the strength on the jointed beams. Applicability of the lap scarf joint with wooden dowels for reparation of damaged structural members in historical trussed roofs is discussed in terms of the joint's strength and stiffness. Moreover, authenticity and aesthetics of such prosthesis for historical timber structures was explored through testing two different types of lap scarf joints i.e. two-face and three-face joints.

Streszczenie

Artykuł poświęcony jest analizie pracy mechanicznej połączeń zakładkowych z zamkiem ukośnym i drewnianymi kołkami, które są powszechnie stosowane podczas prac naprawczych uszkodzonych belek w konstrukcjach zabytkowych. Przeprowadzono testy badawcze oraz analizę numeryczną w celu sprawdzenia parametrów mechanicznych, takich jak sztywność oraz wytrzymałość tego typu protez. Badania koncentrowały się na analizie pracy połączeń w warunkach obciążenia złożonego, gdy element poddawany był działaniu naprężeń ściskających i zginających, oraz rozciągających i zginających. Prowadzący testy starali się symulować rzeczywiste warunki obciążenia, jakim poddawane są zabytkowe drewniane wiązary dachowe, takie jak połączone naprężenia ściskające i zginające oddziałujące na krokwie lub naprężenia rozciągające i zginające oddziałujące na belki wiązarowe. Przeprowadzono testy połączeń belek w pomniejszonej skali, poddanych czystemu zginaniu, obciążeniom złożonym ściskającym i zginającym oraz obciążeniom złożonym rozciągającym i zginającym. Następnie przygotowano Model Elementów Skończonych, na którym zweryfikowano wyniki otrzymane w eksperymentach oraz posłużono się nim do określenia wytrzymałości połączonych belek. Możliwość zastosowania połączeń na zakładkę z zamkiem i kołkami drewnianymi do naprawy zniszczonych elementów konstrukcyjnych w zabytkowych wiązarach dachowych analizowana była pod kątem wytrzymałości i sztywności złącza. Ponadto przeprowadzono analizę autentyczności i kwestii estetycznych użycia tego typu protezy w zabytkowych konstrukcjach drewnianych, testując dwa rodzaje złączy na zakładkę z zamkiem – o dwóch licach i o trzech licach.