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NUMERICAL ASSESSMENT OF BEHAVIOR OF A HISTORICAL CENTRAL EUROPEAN WOODEN JOINT WITH A DOWEL SUBJECTED TO BENDING

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Abstract. *In the Central Europe there are many historical constructions that contain various historical joints that do not contain any metal connectors. The lack of engineering standards for their design due to their reconstruction calls for detailed analyses of their behaviour. Therefore, the goals of this work were: a) to develop a contact finite element model of the "oblique joint with a dowel"; b) to numerically analyse the joint when loaded in 3-point and 4-point bending tests. The FE model was 3D and enabled to study hypothetical scenarios at different geometries, used materials. The FE model assumed orthotropic material properties of wood (Norway spruce) and elastic region of deformation, the contact was flexible-to-flexible and symmetric meaning the all parts of the joints could experience deformation. Results from numerical analyses revealed an influence of the a dowel vertical position in respect to the beam neutral axis on stiffness. The stiffness of the beam with joint increases as the bolt lowers to the tension side of the bending. The joint is very sensitive to geometrical intolerances since the contact oblique faces may substantially change the stress/strain transfer in joined pieces. The analyses also predicted that the lower angle of the oblique faces may increase the stiffness of the joint due to the friction. The lower angle, though, brings technological issues of reconstructions in-situ, so the compromise between length and stiffness must be chosen.*

INTRODUCTION

Assessment and design of mechanical behavior of wooden joints used in historical constructions such as churches, castles etc., is of high interest in the Czech Republic, the Central Europe eventually. The reasons are a) a high number of historical structures in the area of Central Europe and their significance to the national heritage; b) a lack of information about their behavior when mechanically loaded, and c) a lack of design codes for the practical structural design of the historical joints when their reconstruction or replacement is inevitable. Before any design code for such joints can be created, it is necessary to carry out the fundamental investigations on joints' properties and their mechanical behavior. The global aim of this study was to perform such an analysis of one typical historical joint. Generally, there are three approaches used to achieve this aim: a) experimental tests; b) analytical calculations, and c) numerical modeling. Experimental and analytical assessment of wooden joints' behavior is a main source of data collection used in research and engineering practice of joints and, moreover, serve for verification of numerical analyses. The analytical approaches especially in the context of dowel-like joints are mostly based on the Johansen theory and are incorporated in the standards such as Eurocode 5 [1]. Analytical and numerical models for evaluating the bolted connections in wood from 1950's up to 1997 is covered by a comprehensive review [2] and thus is omitted here. More recently, using FEM and digital image correlation (DIC) for analysis of the fracture of wood in the pinned and moment-resisting joints was presented [3, 4]. Using the same combination of techniques for comparison of strain fields around the system of bolts and gaining valuable data that revealed non-uniform strain distributions contributing to the joint failure was carried out in [5]. In [6], an experimental analysis of wooden composite beam connected by dowels welded into the beam layers by a rotation welding was performed. It was shown that a higher number of dowels affected more the beam stiffness than the ultimate load. The finite element method (FEM) and the boundary element method (BEM) are the most popular numerical methods in the research of wooden joints. It is illustrated by reviews ranging numerical models of joints in years 1990 to 2002 [7, 8]. The use of numerical modeling in joints helps to both to asses locations of joints that are difficult to access and save time in discovering the crucial problems of the joint meaning the one can analyze broad range of joint hypothetical scenarios when the analysis is parametrically scripted [9]. In terms of dowel joints, there are many FE techniques implemented in many softwares an analyst can currently use, but in fact there are four basic model categories – solid bolt, coupled bolt, spider bolt and no-bolt [10,11]. An incorporated linear elastic fracture mechanics (LEFM) into the load-bearing FE analysis of glulam bolted joints was also presented [12]. The authors revealed two main characteristics for beams in bending: a) the farther the bolt is from the beam edge (vertically), the higher is its load-bearing capacity; and b) the closer the bolt is to the beam center (horizontally), the higher is the load-bearing capacity. Comparison of these four bolted joints models showed that the solid bolt model most accurately predicts the physical behavior of the connection [13]. The other models exhibited still acceptable results and were computationally less expensive, which makes them valuable for certain applications for the nail and screw connections as showed for instance in a recent study [14]. In spite of enormous amount of FE analyses of bolted and other modern engineering joints, the numerical and experimental research of historical wooden joints with oblique faces is rather rare. Traditional timber scarf joint with inserted key used in bridges was analyzed in [15, 16]. The authors found out that the joint can be successfully modeled using the contact FE analysis based on comparison of stiffness with the experiments. A numerical analysis of bolted connections with help of non-linear FEM simulations that was verified by full-scale experiments was showed in [17]. Validated FE models revealed that the geometrical intolerances and dowel diameter strongly influence displacement of the whole structure and stresses developed in the joint members and, therefore, should be of interest when building in.

The goal of this work was to assess historical timber joint with oblique faces and dowel used in historical constructions in the Czech Republic with help of numerical approach. The specific objectives were: a) to build a 3D contact finite element (FE) model of the joint and verify it using experimental data; b) to perform FE sensitivity analyses to find out how particular geometrical parameters influence the joint stiffness.

1 MATERIALS AND METHODS

The geometry of the analyzed joint is depicted in Figure 1. The joint was further numerically examined in terms of the influence of various geometrical parameters (pin position, pin diameter, angle of the oblique face, and friction coefficient) on the beam stiffness – sensitivity study; b) experimental tests including the 3-point and 4-point bending tests accompanied by both the contact displacement sensors and the optical non-contact technique based on digital image correlation (DIC) (for this part of the work, see Kunecký et al. in proceedings of the SAHC2014 conference).

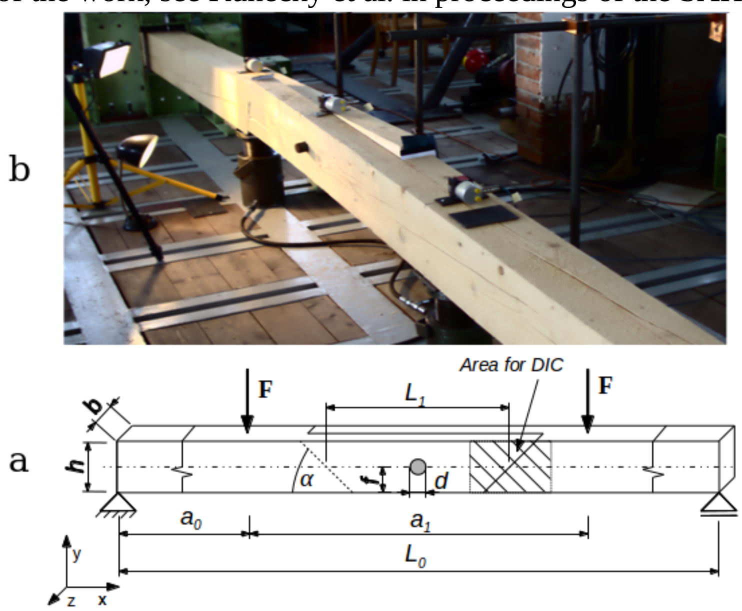

Figure 1: a) Geometry of tested beam and joint with oblique faces in 4-point bending test; b) tested sample of full-scale (testing was carried out with specimens oriented upside down)

For a numerical assessment of the joint with oblique faces the FE model was built using the Ansys Parametric Design Language (APDL, v.14.5). The FE model was assumed as valid for the sensitivity study once satisfactory consistency with the experimental data was achieved, ie. the agreement was found by comparing numerically predicted MOE with the corresponding MOE obtained experimentally. The FE model of the joint is depicted in Fig. 2. The model was virtually cut into the primitives to create conditions for a higher quality mesh created by sweeping technique. The beam geometry was also sliced at the positions where the boundary conditions were applied to assure the constrained nodes have precisely the positions as required for computation of MOE. The FE model was locally refined at the joint elements' contact areas (around the dowel and at oblique faces). The model consists of ca. 15 000 FE's, which reduces computational time to 3 minutes at standard computing machine (processor i5, 8 cores, 16 GB RAM).

The contact was defined between the dowel and the hole in one half of the beam, the other half of the dowel was constrained to the beam. This was necessary for achieving a convergence because the dowel could not experience a rigid body motion. The other contact areas were defined at the oblique faces that are assumed to carry most of the load when beam is loaded in bending mode from the top. The contact was defined as 3D surface-to-surface, symmetrical (each piece was target as well as contact one), with an augmented Lagrange formulation where normal stiffness factor was kept for all analyses at 1.0. The elements used for the contact were CONTA174 and TARGE170, and for a volumetric mesh the octahedral element SOLID186 was used.

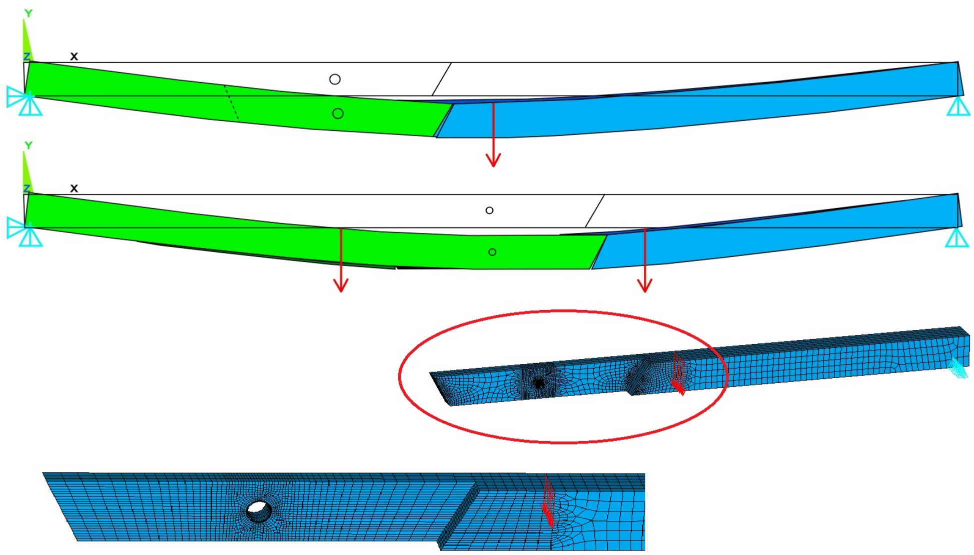

Figure 2: FE model of three-point bending and four-point bending; detail of the FE mesh

Wood was modeled as an elastic and fully orthotropic material and the dowel was assigned the structural steel properties (Tab 1.). Stiffness parameters used in FE analyses were derived from the MOE that was measured in a solid beam with a cross-section of 0.2 x 0.24 m^2 and from the material properties found in literature which examined the Norway spruce from Central Europe [18]. The measured MOE resulted in 7940 MPa. This value was divided by the mean MOE from [18] which was 8210 MPa, so the resulting conversion factor *k* equals to 0.967.

Table 1: Material properties of wood used in FE computations.

Material	MOE	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
Norway spruce (from [18])	8210	13650	789	289	474	573	53	0.014	0.557	0.014
Norway spruce^k	7940	13201	763	279	458	554	51.2	0.014	0.557	0.023
Steel	-	210e3	-	-	80770	-	-	0.3		

E_L, E_R, E_T – normal elastic moduli [MPa]; G_{LR}, G_{LT}, G_{LR} – shear elastic moduli [MPa]; ν_{LR}, ν_{LT}, ν_{RT} – Poisson's ratio [-], k = 0.0967, Coefficient of friction μ = 0.3;

2 RESULTS

The results of experimental measurement indicate that the MOE depends on a dowel vertical position, see Table 2. All values of MOE are actually "apparent" values of MOE because the jointed beam was not continuous. The highest MOE in three-point bending mode was achieved for the joint with a dowel located in the middle (mean value is 9.33 GPa) and the lowest MOE was obtained for joint with dowel at the top position (mean value is 7.36 GPa). The mean value of the top position of the dowel is strongly affected by statistically significant weak wood that was present in the specimens and was caused by knots and drying cracks. The middle value of mean MOE was achieved when the dowel was in the bottom position (8.58 GPa). The mean value of MOE in four-point bending was 8.40 GPa, which was predicted by the FE analyses with very low relative error depending on the material of dowel (2.73% when steel dowel was used, -0.53% when wooden dowel was defined in the FE model).

Table 2: Results from FE analyses of the joint with oblique faces and corresponding experiments.

Test mode	Dowel position	FEA MOE [GPa / %]	Exp. MOE [GPa]
3-point bending	Bottom Middle Top	9.38 (9.3) 9.44 (1.2) 9.25 (25.6)	8.58 9.33 7.36
4-point bending	Middle	8.63_S (2.73) 8.35_W (-0.59)	8.40

The relative errors of FE model of the joint were relative low if outliers values are not considered (Tab 2.) and, therefore, the FE model can be used for the further sensitivity analysis (SE). The coefficients of determination (R2) for all numerical predictions in SE's were relatively high (most often more than 0.9, occasionally it achieved 0.7-0.9); therefore they will be omitted in the further text.

The first SA (SA1) examined the joint's MOE dependence on the dowel diameter (*d*). This dependency for both steel and wooden dowels and for angles 45° and 63° loaded in both modes is showed in Fig. 3 left. The apparent MOE's increase in all configurations as *d* increases. Apparent MOE's are higher when a steel dowel is used and the mean relative difference r_{SW} equals to 2.5% which is a negligible effect. When *d* achieves higher values ($d > 65$ mm), the MOE starts growing rapidly for both 63° and 45° angled joints with the steel dowel. The relative difference between the lowest and the highest obtained values in these cases is approximately r_{LH} = 10.2%. For cases Wood 45_4 and Steel 63_4 the r_{LH} was about 3.3%. It is necessary to say that dowels with $d > 60$ mm are not used in real constructions; therefore such analysis provides only hypothetical results.

The second SE (SE2) examined the influence of the dowel vertical position on MOE (Fig. 3 right). SE2 was carried out for the same parametric configurations as the SE1. Fig. 3right shows that for each bending mode the MOE responses in a different way. For the three-point bending the maximal MOE is achieved when the dowel is in the middle of the joint's height. This is due to the fact that the dowel contributes to bending stiffness of joint by carrying the shear stresses that are maximal in the beam neutral axis located at the *h*/2. From the reaction forces' orientation standpoint, their resultants are closer to the neutral axis and the area at oblique face at which the stresses act increases. The numerical models exhibit slightly different behavior than experiments (dowel at bottom exhibited higher MOE than dowel located at the top), but are in agreement to findings of Fajman [19] who analyzed forces for the same joint. The simulated r_{LH} was for the three-point bending test for both materials approx. 2%. The difference between the steel and the wooden dowel expressed as r_{SW} is approx. 1.8%. In case of the four-point bending test, the predicted MOE is the highest when the dowel is located at the bottom position and is the lowest when the dowel is at the top position (6 cm above the neutral axis). The same behavior was found for both 63° and 45° angled joints. The reason why the bottom position makes the joint stiffer is that the dowel works as the center of rotation, so the lower the dowel is, the more it forbids the joint opening at its bottom side, which, consequently leads to an increase of MOE. As for three-point bending, the joint with wooden dowel has lower MOE (r_{SW} is ca. 4%).

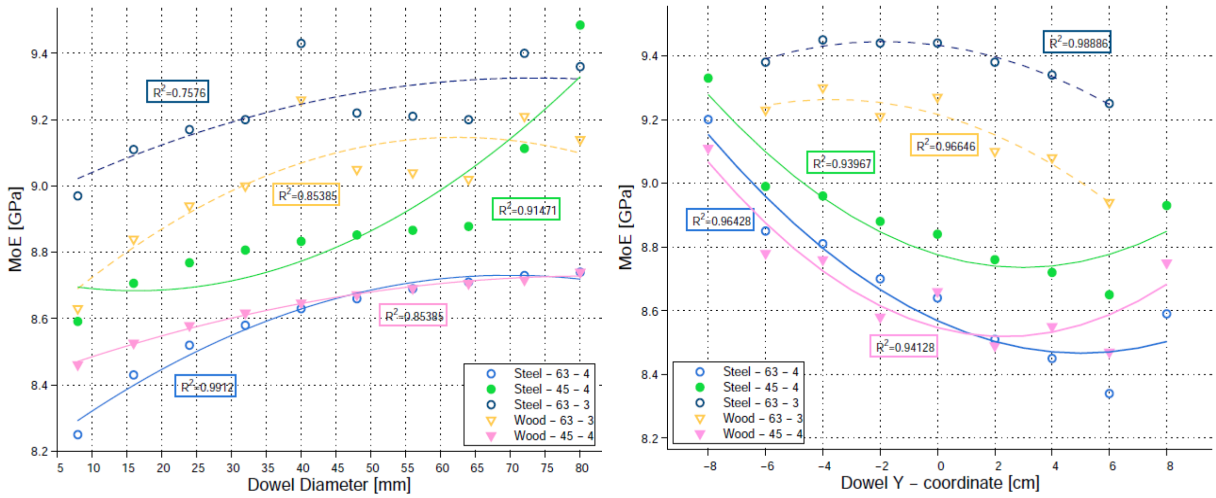

Figure 3: Results from the FE analyses; MOE depending on dowel diameter (left) and MOE depending on vertical position of dowel (right)

The third SA (SA3) investigated the influence of the angle on MOE and is depicted in Fig. 4 left. For both modes of bending and for both types of dowels, the MOE decreases as the angle of the oblique face increases. The reason for such behavior lies in contact of oblique faces and horizontal force (F_x) acting at the dowel. The contact area shrinks with the increasing angle and at the same time the F_x rapidly increases. For instance, the F_x for joint with 24° angle is 2.6 times lower than for the joint with 80° angle. Therefore, for the joints with bigger angles the material of the dowel is the more crucial parameter. However, the lower angles of the joint in real constructions can be often limited by space and technology of work. The roof trusses primarily require as short connections as possible and their manufacture is often driven by ease of work. Looking at the r_{LH}, the three-point bending and joints with 63° and 45° is approximately 6.9%, and 8.3% respectively.

The fourth SA (SA4) investigated the influence of a friction coefficient on MOE and is depicted in Fig. 4 right. The coefficient of friction (CoF) positively influences the MOE, although very little (r_{LH} is approx. 2.9%). The CoF exhibited the lowest effect on joint stiffness in the presented model. The reason why friction does not contribute much to the joint stiffness is that the FE model has idealized the geometry, so the contact at oblique faces mostly occurs at the very top, the rest of their length is experiencing opening. In the experiments, on the other hand, the opening was lower and the friction had more impact on stiffness. This could be illustrated by failure mode of several specimens which experienced a crack in the half of the oblique face because the joint parts could not slide further on each other due to the geometrical intolerances and consequent increased friction (see Fig. 4 right where failure at oblique face is shown).

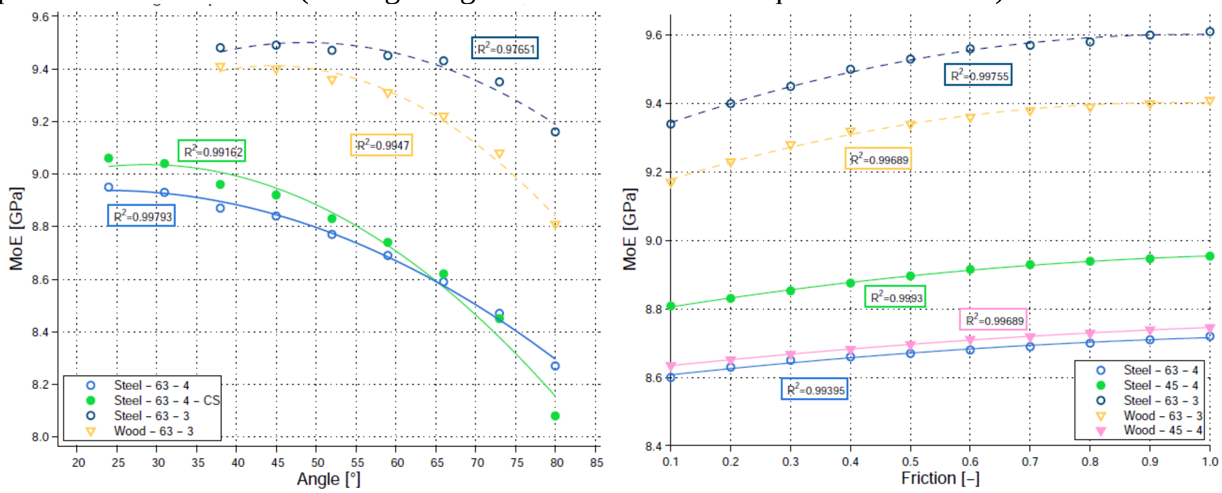

Figure 4: Results from the FE analyses; MOE depending on oblique face angle (left) and MOE depending on friction coefficient (right)

3 CONCLUSION

Sensitivity FE analyses proved the dependence of joint stiffness on geometrical parameters of the joint. The highest influence on MOE was found for the angles of the oblique faces and the maximal difference ranged between 6 to 8% (6-8%). The vertical position of a dowel exhibited lower influence between 2-4% and the impact of dowel diameter and friction on stiffness when real range is of concern was about 3%. The FE model of the joint with dowel and oblique faces was experimentally verified and consequently offered decent possibility of “what-if” scenarios in elastic range of deformation (linear deflection). This model enabled to find optimal geometric parameters of the joint.

4 ACKNOWLEDGMENTS

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