18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 815–824
Paper #226

INFLUENCE OF GEOMETRIC PARAMETERS ON THE STIFFNESS OF TRADITIONAL DOVETAIL TIMBER JOINT

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Abstract: *The paper presents the development of numerical modeling for a traditional dovetail timber joint. The objective is to find the influence of its geometrical properties on the mechanical stiffness of the joint as well as to assess the main problems and limitations faced during the numerical modeling of the structure. An experiment with a replicated timber joint was used to validate the model. Material properties were ascertained and contact adjustment was made. Parametric study was performed: two angles of the joint beams (α, β) were varied. Suitable ranges of the angles for each type of loading were found. Main limitations and problems present in the modeling are depicted in the discussion.*

Keywords: ***Historical construction, timber joint, numerical modeling.***

1. Introduction

1.1. Motivation

Historical buildings represent for contemporary professionals and researchers a seamless source of inspired engineering solutions which, if opportunely applied, provide feasible modern applications. The development of such practical potential, however, cannot prescind from an accurate exploration of the peculiarities of modern and traditional realities and an adequate assessment of their interaction (Vinař et al., 2010). From this perspective traditional carpentry and timber assembly techniques require a deeper understanding of the context in which they were developed in order to address the safety and functional requirements imposed by current design practice. The following considerations should be made:

The making of carpentry joints in the past was commonly grounded on empirical rules and its design strictly context-specific. The consequent lack of experimental and analytical evidence interferes with the establishment of reliable behavior models and the outlining of recommendations for rehabilitation or strengthening of timber structures. The result is a knowledge gap in the building codes and international standard that necessitates integration.

The heterogeneity of timber joints characteristics constitutes a true challenge for modeling process: the variation of geometrical parameters and the material nonlinearity imposes the development of a comprehensive methodology aimed at reducing standardization errors and at overcoming modeling limitations to a satisfactory extent.

Although research concerning specifically wood connections is somewhat limited, considerable leaps forward are being made (Burnet at Al.). In Czech Republic, for example, the *´Design and Assessment of Timber Joints of Historical Structures´* project, funded by the Ministry of Culture (DF12P01OVV004, February 2012), aims at tackling the above mentioned issues with extensive research in traditional joint testing and implementation of their mechanical behavior through experimental approach and numerical modeling, this study being one of its preliminary step.

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1.2. Objectives

The main objective of the analysis is to individuate and quantify the influence of the variation of parameters of a traditional dovetail timber joint and develop a suitable numerical model for a specific case.

The objectives are:

- To find the influence of parameters of geometry and determine the main limitation of modeling

- To understand the behavior of the joint under load, especially for further experimental testing leading to determination of its bearing capacity

1.3. Oblique dovetail halving joint

The joint under analysis is an oblique dovetail halving joint (Fig. 1). It combines two different carpentry methods, dovetailing and halving, to provide for an improved performance in specific building components such as roof trusses. Such combination, in the middle Ages, was frequently adopted for right-angled or oblique joints subjected to particularly preponderant axial forces.

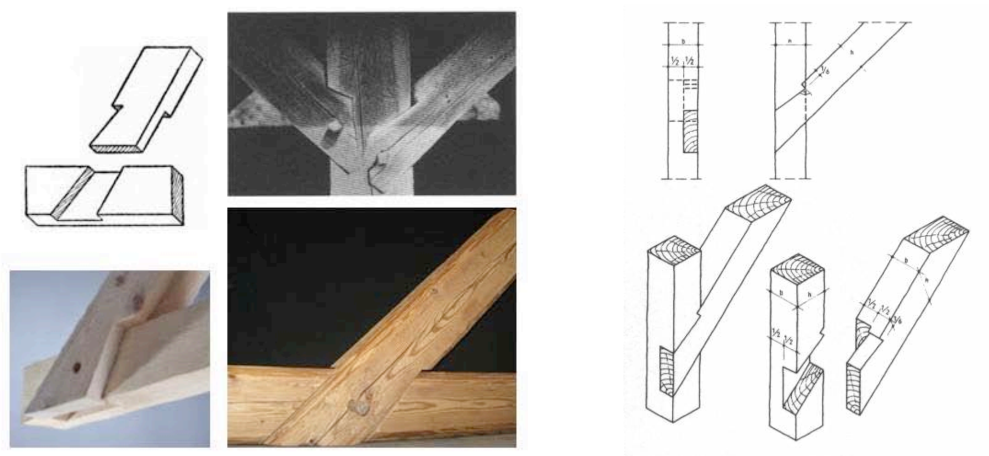


Fig.1: Examples (left) and typical geometry (right) of oblique dovetail timber joint (Gerner et al., 2003)

Dovetailing is a common technique widespread in woodworking joinery which consists in shaping the end of one member as a dovetail pin and in cutting a matching slot in a second member to be connected in order to ensure good interlocking. Such joint presents mainly resistance to pulling.

Halving consists in cutting half the depth of the timber section. This is one of the simplest methods of connecting two pieces of timber, especially where it is desired to make frames and bracket supports for either inside or outside use.

In the oblique dovetail halving joint the connecting members are at an angle to each other. Such method is mainly used for bracing of frames and can be occasionally observed with both its sides dovetailed.

1.3.1. Typical geometry

As a prerequisite for modelling it is necessary to individuate the main geometrical characteristics of the joint. A geometrical standardisation is possible by taking into consideration the ´golden rules´ used by handcraft men directly on site. Such rules, found in both modern literature and historic manuals, outline the general proportions with which cuts should be made in the timber elements.

The diagram in Fig. 1 shows a schematic layout of an oblique dovetail halving joint (Gerner et al., 2003). The vertical beam presents a cut of depth equal to half its breadth and two non-parallel oblique cuts on the height side to allow for interlocking with the dovetail. The oblique beam has a longitudinal halving for a length equal the height of the vertical beam; the halved section has a right-angle triangular shape cut of base equal to one sixth of the height of the oblique beam section and opposite vertex being the corner of the beam itself.

2. Methods

2.1. Outline of the work

A parametric FE model is presented to clearly explore the reaction of the joint to different loading phases. Experimental techniques are thoroughly applied to appropriately adjust and validate the model. Specific experiments are performed: material testing is required in order to determine mechanical parameters and the contact surfaces' behavior (wood-steel, wood-wood) is analyzed to specify contact characteristics in the joint. The paragraphs below outline the joint assembly and material tests and the necessary contact adjustment. The model is verified by comparing and cross-checking the measured and modeled values of its mechanical behavior. A sensitivity analysis, for different geometric parameters of the joint, is also performed.

2.2. Experiments

2.2.1. Dovetail joint experiment

The tested joint is prepared by assembling two beams of old dry timber coming from a historic roof built during the eighteenth century (see Fig. 2). The general layout and the geometrical details of the tested joint are shown in Fig. 3. Both beam 1 and 2 present a cross section of 175x150mm and intersect at an angle of 50°. Beam 1 is a 928 mm long timber element showing on one side a cut 216 mm wide at the top and 245 mm wide at the bottom of the beam. The difference between the two measurements reveals that the two sides of the slot in the beam are not parallel but one is inclined about 10° more than the other one with respect to the vertical. Beam 2 is 880mm long with a projection on the vertical plane of 743 mm. The height of the halved section is 182 mm and presents a cut at 60° with the horizontal on the leeward side of the beam. A hole of about 30 mm of diameter, located at the point of intersection of the beams axes, allows for dowel interlocking.

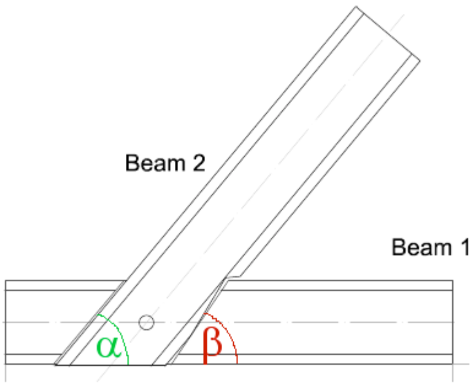
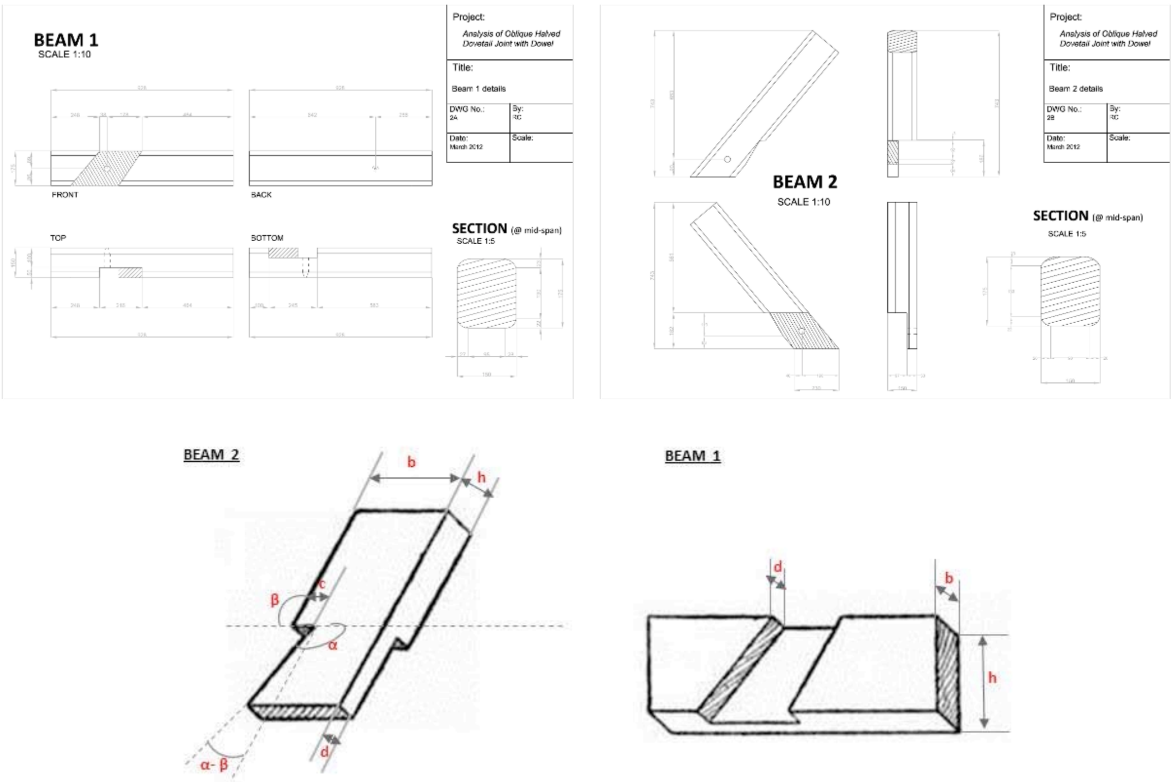


Fig. 2. The tested timber joint (left), simplified geometry with important parameters (right)



		Theory	*Measured*
BEAM 1	*b (mm)*	-	150
	h (mm)	-	175
	d	0,5b	0,333b
BEAM 2	*b (mm)*	-	230
	h (mm)	-	175
	c	0,167b	0,152b
	d	0,5h	0,353h
	α	55°	60°
	β	45°	50°
	α-β	10°	10°

Fig. 3. Geometry of the experimental joint (top) compared with literature data (bottom)

The table shown in Fig. 3 outlines the ratios between the relevant dimensions of cuts on the two timber members. Such data provides useful information for quantifying the divergent ranges of geometrical parameters of the analyzed joint. It can be seen how the measured joint differs slightly from the theoretical geometry (see par. 1.3.1) mainly due to manufacturing constraints and adaptation of dimensions during the assembly phase.

During testing the joint is subjected to cyclic loading produced by a servo hydraulic MTS actuator (cylinder) with a capacity of 25 kN, connected to a steel frame. The rotational response of the joints is measured indirectly by means of the potentiometer Megatron SPR 18-S-100 (5kΩ).

During the session the displacement of beam 2 is recorded to be ±10 cm. The controlled amplitude of such displacement is increased at every cycle with a constant step equal to 4 mm. The frequency of each cycle is equal to a value of 0,1 Hz.

2.2.2 Determination of material properties

Specimens of dimensions 30x30x30 mm were cut from the unloaded sections of the tested beam. Compression was applied by using standard testing machine with constant strain rate 0,0002/s. The magnitude of such loading conditions and the related sample responses are shown in Fig. 4.

Unfortunately a number of constraints derived from the nature of the empirical analysis precluded an exact determination of all those coefficients needed for modeling the orthotropic nature of wood (E_x, E_y, E_z, G_{xy}, G_{yz}, G_{xz}, μ_{xy}, μ_{yz}, μ_{xz}). Therefore material parametric values available in the literature, typical for the type of wood tested, are integrated in the implementation of the model (Požgaj et al., 1997). Although measured data reflect partially the general trend presented in the bibliographical references (E_x:E_y:E_z=27:2:1) the absolute values obtained during testing considerably diverge to standard ones outlined in *Picea abies* (possibly due to 250 years old dry state of specimen). The approach pursued, which will be described in greater detail in the next sections, consists in scaling the unknown parameters G_{xy}, G_{yz}, G_{xz}, μ_{xy}, μ_{yz}, μ_{xz} accordingly to the ratio between measured Young's moduli and theoretical values (Tab. 1.). The axes considered during modeling are respectively XYZ ~ LRT.

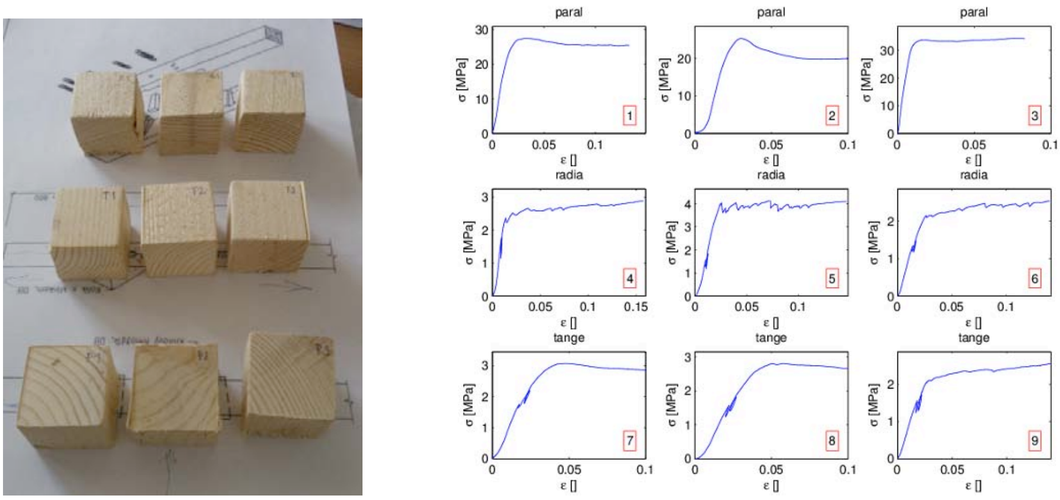


Fig. 4. The samples of old wood tested (parallel to grain/longitudinal, radial, tangential orientation of annual rings)

It is important to underline that the results of testing are strongly influenced by the location of the specimen's cube in the original beam and its orientation. The number of annual rings in the cross-sectional area also show to have a certain impact on the measured moduli. In order to overcome this interference and as there exist the methodological need to model the wood as a continuum these values were averaged to the mean number of annual rings.

Tab. 1. Material properties used in the modeling of the timber joint [MPa]

E_x	E_y	E_z	G_{xy}	G_{yz}	G_{xz}	μ_{xy}	μ_{yz}	μ_{xz}
2180	186	92	92	12.5	150	0.023	0.014	0.687

2.2.3 Experiments for contact adjustment

In order to appropriately determine the contact adjustment, the wood was tested by the following (see Fig. 5):

a) a 25x25mm steel cube pressing the sample

b) a 30x30x30mm timber cube (30x30x30 mm) cut from the historical material available is pressed against a wood joist. Orientation of fibers is set to be longitudinal pressured to radial orientation of joist.

In these experiments force-deflection curves are recorded.

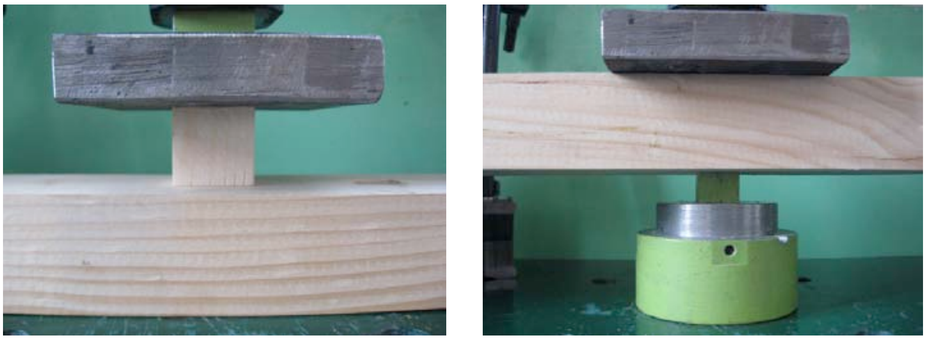


Fig. 5. Contact experiments

2.3 Numerical modelling

2.3.1 Model description

The FE model is built by using ANSYS finite element software. For simplification of the problem and in order to avoid continuous divergent solutions only few elements were considered. The quadratic SOLID95 hexahedral element type was chosen. The model is shown in Fig. 6.

It has to be noted that the timber dowel shown on the tested joint is not considered in modeling for the following reasons:

- the paper focuses on investigating the role of generic geometric parameters of the dovetail joint. The presence of the dowel, by further restricting localized movements, would produce deformations with plastic/cracking behavior, which falls outside the concern of this preliminary study on wood.
- the validation of the proposed model is mainly based on bending and in this perspective the role of the dowel would not have considerable significance.

The model presents orthotropic material properties without plasticity because of lack of experimental data about plastic behavior along the tested sample (results from the material testing are valid only on the continuum level, however, locally will be probably the deformations higher near the jaws). All the DOFs are removed according to those of the tested joint (see Figs. 2 and 6). Three types of loading are considered: tension compression and bending. The parameters varied for the purpose of this study were the two angles *(α,β)* shown in Fig. 2, which mostly influence the behavior of the structure under loading. Static friction between the beams was set to be 0.5. A 2mm gap between the two beams of the joint was also modeled.

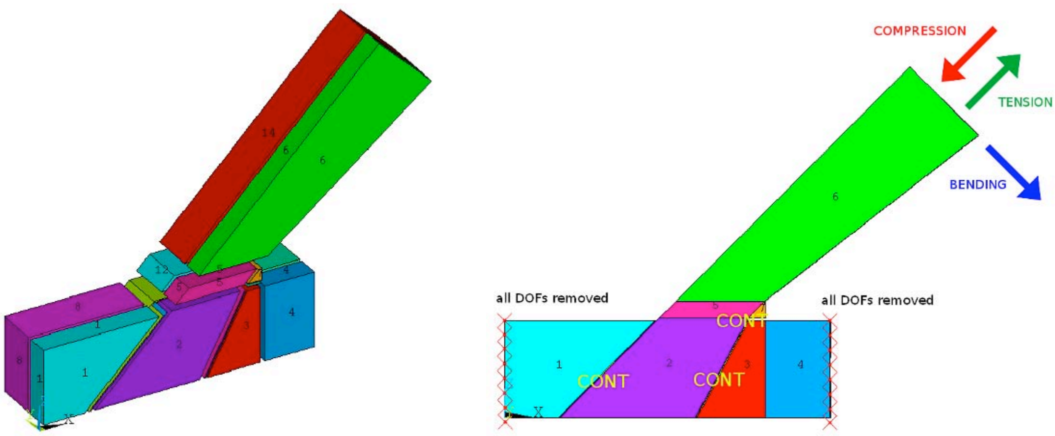


Fig. 6. The finite element model of the joint (left), loading and contact description of the joint (right)

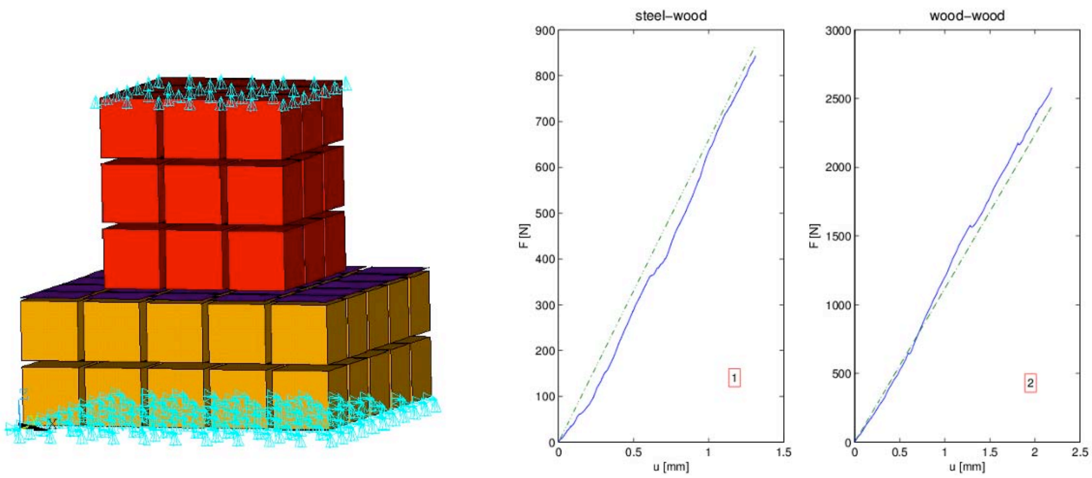


Fig. 7. Contact model – shrinked elements (left), contact validation results (right)

2.3.2 Contact adjustment

To understand well the behavior of contacts between the beams under static conditions, an additional simple FE model was created (see Fig. 7). Surface to surface contact was chosen for the analysis using quadratic contact elements CONTA174 and TARGE170. Augmented Lagrangian formulation of the contact was used with some additional adjustment of the contact parameters. Contact elements were precisely inserted between the 3D elements and node positions were carefully reviewed. The comparison between numerical model and experiments was shown in Fig. 7. The first section of the graphs, representing the state before cracking the tensioned top grains of the joist was neglected (because this phenomenon was not considered in the numerical modeling). The contact behavior was considered to be relatively precise and was applied to the dovetail joint model (see Fig. 6 CONT).

3. Results

3.1 Validation

The model was loaded in bending as per the above mentioned joint test. As discussed before the role of the dowel was considered to be negligible for this type of loading. Comparison between the results from experimental measurement and numerical computations is presented in Fig. 8. It stems out that the bending stiffness of the numerical model is higher than that of the measured joint. However such discrepancy can be justified by considerations of different nature:

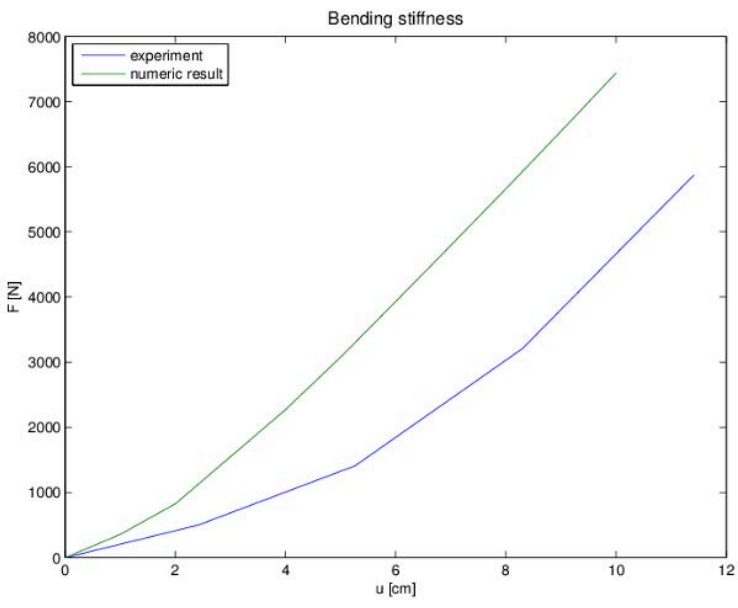


Fig. 8. Comparison between numerical model and experimental data

- the problem cannot be exactly modeled because of the heterogeneity of wood and the lack of an appropriate number of material testing
- model does not consider the drying cracks that can be instead observed on the historical beam
- the simplified model pursued by this study does not purposely take into account the plasticity of wood
- the surface of the beams on the sides of the joint cuts is made using traditional techniques and therefore not completely planar
- cracking of wood heard during the experimental testing cannot be included in the numerical model

Because of these reasons it is possible to say, that the validation is not made in the meaning of preciseness, but in the meaning of the context. The paper is focused on determination of the role of the geometry of the joint and not on acquisition of precise numbers absolutely (it is, in fact, not possible using FE but only using a set of experiments).

3.1 Parametric study

In the parametric study the two angles (α,β) were varied in the range of α ranging from 30° to 70° with a step of 5°. β is varied from *actual* α+2°to α+22° with a step of 5°. The reason is clear – the dovetail should always have higher β angle than α angle. The tensile and compressive loading was applied in the axis of the loaded beam 2. Bending was always perpendicular to this axis. Results from the simulations are shown in Figs. 9-11.

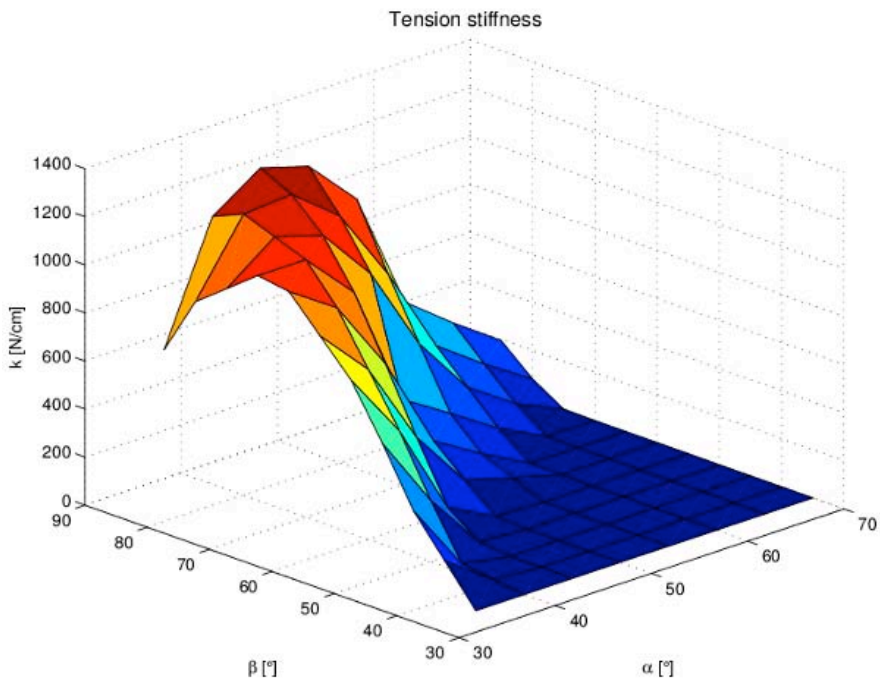


Fig. 9. Beam loaded in tension in axis of the beam 2

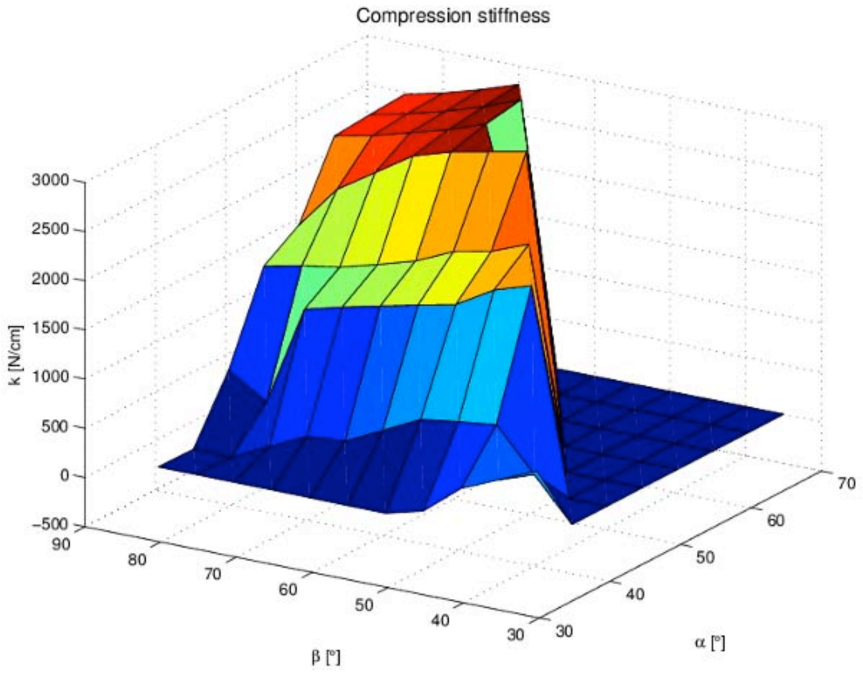


Fig. 10. Beam loaded in compression in axis of the beam 2

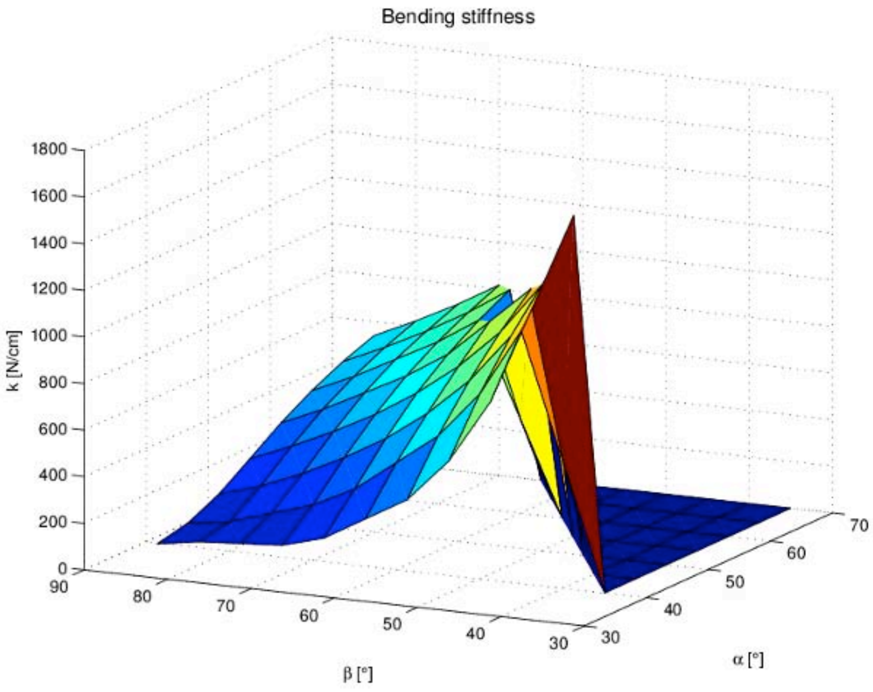


Fig. 11. Beam loaded inbending perpendicular to the axis of the beam 2

According to the computations made for beam two being loaded in tension, it is best to use 45° angle of the beam with nearly right angle β. For the compressive test, it is the best option to choose higher than 45° of angle α with small difference between the α and β. If the beam 2 is supposed to be loaded in bending it is good to choose only slightly higher β than α. The best solution is always based on the function of the truss in the structure and should be chosen suitably.

5. Discussion and conclusion

Although the results show clear conclusions, they should be read with attention because of many limitations.

- It is clear that for compressive loading the worst values for 30° are caused mainly by the missing timber dowel that enables the structure to slide. The behavior with the dowel will be modeled in future studies already programmed, in order to improve the modeling of traditional joints.
- Compressive stiffness of the joint depends on the size of the hook (see Figs. 1, 2 and 6), probably more than on the geometry itself what clarifies the high stiffness when the angles are higher.
- Material uncertainty and the scaling of material parameters should be advocated: we were looking for trends more than absolutely precise solution. In the future more material samples from more locations of the beam will be measured and averaged. Because the values of Young's moduli are not so well correlated with the values from literature (although such old wood is not mentioned) it is possible, that an error in the measured data could be present. However, because all the measurements were made on the same machine (material, contact), the relative results of the work should be not invalidated.
- Drying - cracking problems will probably remain, however, more fresh wood will be used in the next models.

This preliminary study posed one big question: how precisely it is possible to model the mechanical behavior of traditional timber joints? The answer could be that it showed many uncertainties and unknowns in the modeling and showed the way for ongoing research.

Acknowledgement

The work was supported by a kind sponsorship of grant of Ministry of Culture # DF12P01OVV004 called „*Design and Assessment of Timber Joints of Historical Structures"*. It is also gratefully acknowledged the support of grant #DF11P01OVV002.

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