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Traditional Furniture Joinery from the Point of View of Advanced Technologies

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Abstract

An emerging trend in using new technologies together with classical joints in furniture industry is explained in this contribution. In the past, traditional furniture joinery techniques were mastered by craftsmen or later special machines were developed for this purpose. The industry globalization combined with high demands of production economy has brought enormous decrease in classical joint usage. The application of computer technologies is a current tendency in many branches of industry, both in product development and the actual production. From our point of view, the most suitable technologies for the field of furniture are found within Computer Aided Engineering (CAE), namely numerical simulations - Finite Element Method (FEM) development and Computer Numerical Control (CNC) production. Thanks to these advanced technologies a joint such as a dovetail joint can be employed in furniture construction again. The results are demonstrated on the example of dovetailing in this paper and they are linked to the mentioned technologies. The main purpose of traditional joinery rehabilitation lies in their high strength, added esthetical value and thus higher competitiveness of the final product. In addition, the innovative approach to furniture market can be further upgraded for example by creative design, ready-to assemble (RTA) construction, new materials or new marketing strategies.

Keywords Furniture, dovetail joint, numerical simulation, CNC technology

Introduction

Presented work focuses on demonstration of advanced technologies employment within the branch of furniture industry. Computer Aided Engineering (CAE), represented by Finite Element Method (FEM) and Computer Numerical Control (CNC) technologies are the key tools from our point of view.

Dovetailing is classical furniture joinery with outstanding strength properties. The joint consists of tails and pins, see fig. 1a. The specific construction of the joint, which ensures its self-locking character and consequently considerable strength, requires a demanding technology. This joint is usually made manually or by special machines and devices. The technology of current 3-axis CNC machines makes the manufacture of dovetail joints fast and accurate. However, it also bears some specifics. One of them is the inability of the technology to make sharp inner edges of the milled profile from angle 0° to 180° because of the rotating movement of the cutting tools. This limitation can be removed by boring a hole in place of the demanded edge which results in what is called “the Mickey Mouse ears”, see fig. 1a. CNC manufacturing technologies have a big potential in the fields of furniture production and wood processing, for example in competition with cheap labour. A new manufacturing technology of CNC machines and new composite materials are prerequisites for successful usage of this joint in the current environment of wood and furniture industry (Susnjara, 2006).

Furniture joint testing has been dealt with many times, both by means of experiments and numerical simulations. Mihailescu (2003) analysed various forms of parametric models of joints using FEM. Smardzewski and Prekrad (2002) examined the stress distribution in ready-to-assemble furniture corner joints using experimental testing and numerical simulation. Joščák (1999) used experimental testing to explore mechanical properties of several typical furniture corner joints used for joining composite wood materials.
Zhang and Eckelman (1993) tested the resistance to the bending moment of single-dowel and multi-dowel (glued) furniture corner joints in particleboard.

Material and Methods

Before the manufacture itself a parametric joint is analysed using numerical simulation of mechanical loading, which makes the subsequent geometry and material optimization possible. Thus we obtain the first strength characteristics of the joint and the distribution of stress which allows us to propose modifications. The manufactured joints are analysed by experimental mechanical testing. The objective factors for evaluation will be the strength (capacity) and the stiffness (the ratio of deformation to the bending moment) of the joint when loaded by bending.

The goal is the parametrization of a numerical model and a finite element analysis of mechanical properties of dovetail joints manufactured from 12 mm thick birch plywood. Two parametric numerical models were created, both loaded by a bending moment. These are intended to serve as tools for designing furniture with the joints in question. The models

were solved in the form of a structural analysis. All models are supposed to be compared with, or corrected by, experimental testing.
The contact analysis of the dovetail joint includes another derived material characteristic – the static friction coefficient μ, as follows from this equation:

$$F_t = \mu \cdot F_N \qquad [1]$$

The friction coefficient represents the ratio of the friction force F_t to the perpendicular compressive force F_N affecting the object. In common material tables (Kotlík et al., 2003) or textbooks on mechanics (Meriam, 1978) the wood-wood friction coefficient ranges within 0.15–0.6, or 0.15–0.4 for the dynamic friction coefficient. We based our research on the study conducted by Bejo et al (2000), who measured the coefficients of friction for wood composites Laminated Veneer Lumber (LVL) and Laminated Strand Lumber (LSL). As these wood composites are structurally very similar to plywood, their resulting data are applicable to our numerical model. Their results show that the static friction coefficient in LVL ranges between 0.33 and 0.7 and it is mainly dependent on the contact compression and the direction of fibres both in the specimen and the contact surface.

The methodology for the dovetail joint testing by a bending moment is based on literature – Joščák (1999). Within the framework of this research, the mechanical load was limited to bending in the angle plane – by compression, see fig. 1b), as that is the most frequent and the most critical way of loading furniture corner joints.

Numerical Model

Two parametric numerical models were created for our research. The first model represents a through dovetail joint where the contact between the tail and the pin is not defined. It is an ideally stiff joint, as if glued. The second model is a joint where the contact between the tail and the pin parts is defined, i.e. this is a contact analysis. Boundary conditions, i.e. fixing and loading, are defined so that they correspond to the real conditions of a testing machine while measuring joint stiffness and strength, see fig. 1b). The degrees of freedom UX, UY, UZ are constrained. A 2 mm displacement *d* is applied to the upper edge and at the same time all the nodes of this edge are constrained with the degrees of freedom UX and UY.
Both models are created using the Ansys Parametric Design Language (APDL). As a part of the evaluation of results and with respect to their further comparison with experiments, the universal macro was written in the APDL language; the macro will evaluate the reaction forces at the bottom edge of the joint. The reaction forces are then multiplied by the joint arm so that we could calculate the bending moment of the joint in the angle plane according to:

$$R_{sum} = \sum_{i=1}^{m} \sum_{k=1}^{n} \left(R_{FX}^{n} + R_{FY}^{n} + R_{FZ}^{n}\right)_m \text{ and } M = R_{sum} \cdot v_c \,, \qquad [2]$$

Where $R_{FX,FY,FZ}$ - reaction forces in the individual directions at the constrained nodes [N]
M – the bending moment affecting the joint [Nm]
n – the number of constrained nodes of the bottom edge
m – the number of steps of the analysis

v_c – the moment arm [m].

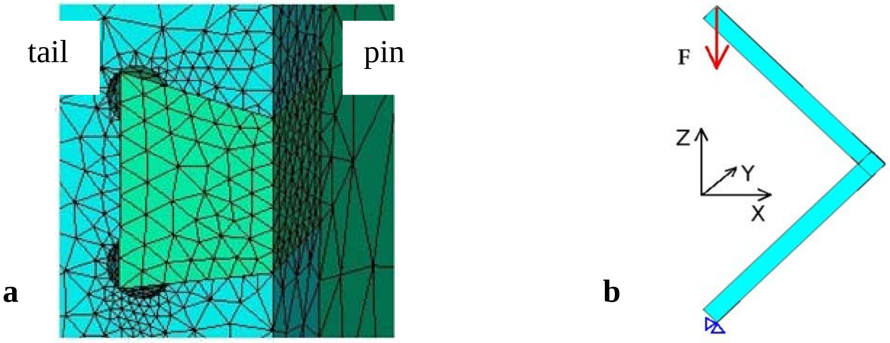

Fig. 1: a) the detail of the FE model, b) loading of the joint in the angle plane by compression

The bending moment of the conducted analyses with various friction coefficients was then transported into a graph for comparison. Experimental verification of numerical models and the results of analyses are important aspects of each numerical analysis. In our case, the numerical models precede the experiments which will be made subsequently using the above mentioned methodology. The used material properties for the numerical model were found in literature – Lang (2002), Highett (1987) and Wood Handbook.

Results and Discussion

From the total deformation and displacement of the joint in the direction of the Z axis we were able to evaluate whether the model had been fixed in the right way and whether the demanded deformation which would occur in the testing machine during experimental testing occurred here. Fig. 2 presents the distribution of von Mises stress in the contact model.

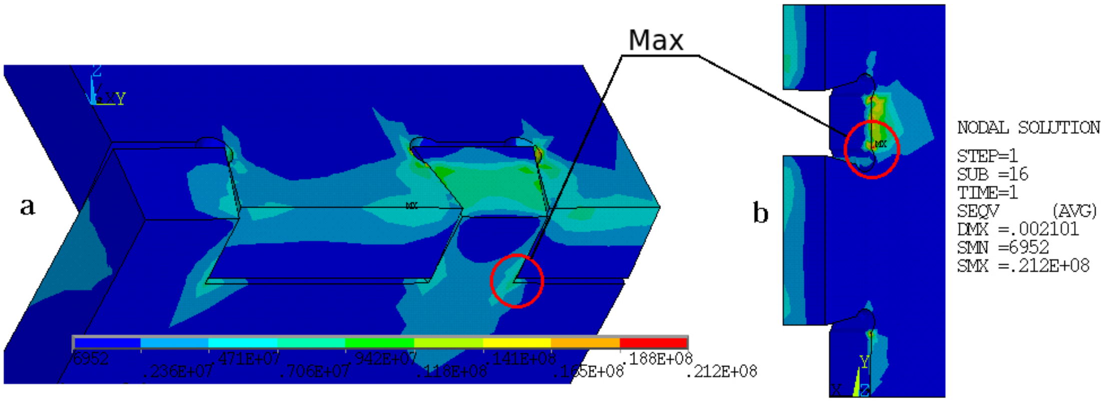

Fig. 2: a) von Mises stress (MPa) in the contact model of the joint made from plywood, b) detail of the distribution of stress (MPa) in the tail

The maximum and the high values of stress expectedly appear in the corner on the base of the tail and in the area of the bored hole in the part with the pin (these values are circled in the picture). Fig. 2 also shows what distribution of stress the joint model produces when loaded. Thanks to the considered contact, it is obvious that there is a higher stress also in the places of friction of both parts – on the sloping areas of the joint (cannot be seen in the pictures). The stress in these places will be the higher, the higher is the joint deformation in the angle plane and the higher is the friction coefficient. Sloping areas of the joint are what determines its stiffness and resistance to deformation. This confirms the well-known fact about the joint that with the increasing angle of the sloping area the stiffness of the dovetail joint increases, especially in the initial stage of loading. However, stiffness can be raised by increasing the angle only to a certain point which is dependent upon the total strength of the joint because by increasing the angle, the geometrical characteristics change considerably and its manufacturability is limited. A bigger angle increases the force necessary for the friction in the pin but at the same time the joint gets weaker and its strength is lowered with respect to the loading in question. Empirical experience and our previous results (Nutsch, 2003; Sebera, Šimek, 2008) show that the optimal angle of pin ranges from 10 to 14 degrees.

The non-contact model has a different stress distribution, see fig. 3. The maximum stress appears on the edge of the bored hole on the basis of the tail, which is the same as in the contact model. However, we can notice that an increased stress also appears on the inner side of the joint, see fig. 3b). For better illustration of von Mises stress distribution contours, the entire non-contact model uses a non-uniform scale instead of a uniform scale of contours, see fig. 3a). The stress distribution shows that this is a different stress field than in the contact model, in which the joint does not behave as if made from one piece. Therefore, the stress can be divided into the compression stress, inside the joint, and the tension stress on the external sides of the joint. Further, we can see that although the joint is defined as glued (stiff), the bored holes are still the places where stress concentrates.

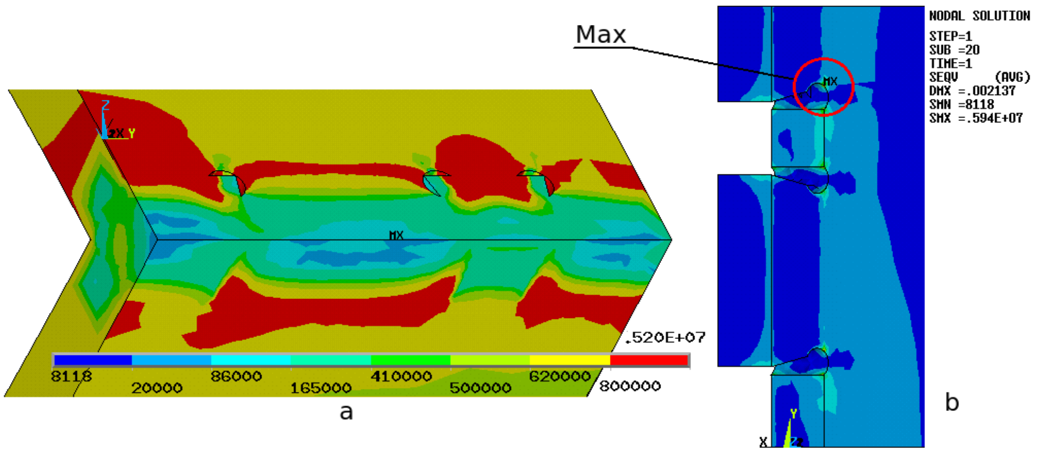

Fig. 3: von Mises stress (MPa) in the non-contact model of the joint made from plywood, a) the entire joint (non-uniform scale), b) detail of the tail (uniform scale)

Furthermore, we can state that the bored holes on the basis of the tail positively distribute stress and thus reduce the probability of a crack initiation. The fact that there is a bored hole in the tail part has a negative impact on the joint in the form of a partial weakening of its geometry but, on the other hand, in this place a higher stress is necessary for a crack to appear than if there was a sharp corner. The evaluation of the joint stiffness according to equation [2] was carried out as the next stage using the above mentioned macro. A graph was drawn expressing the dependence of the bending moment of the joint on the angular deflection, where the slope of the regression equation expresses the actual joint stiffness. Fig. 4 shows the results of contact analyses of the joint with various friction coefficients and also of the glued joint – the non-contact analysis.

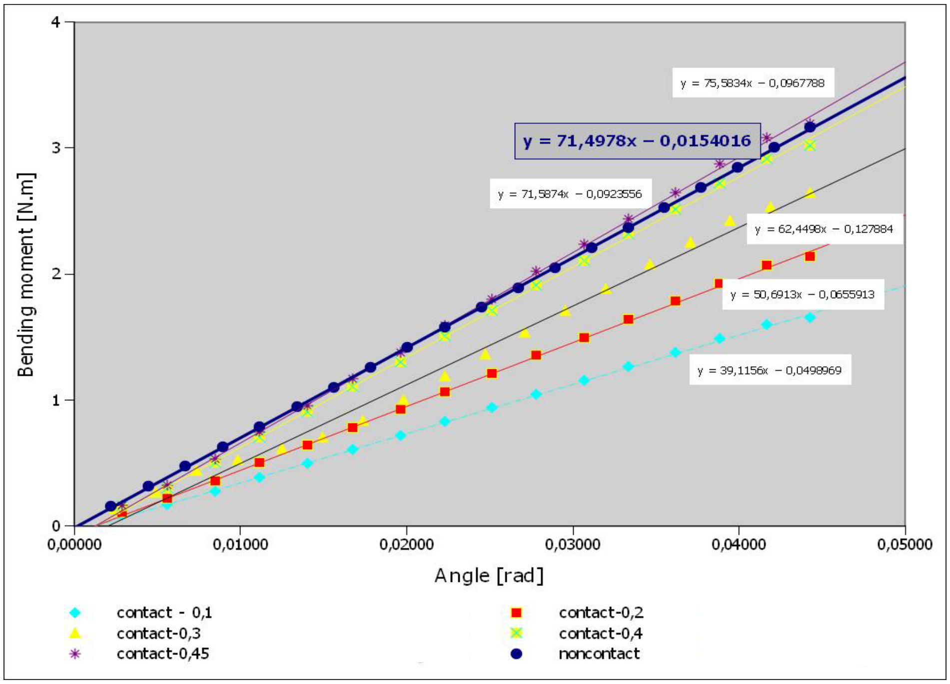

Fig. 4: Dependence of the bending moment and stiffness on the angular deflection (plywood)

It follows from fig. 4 that the resulting bending moment, or the stiffness, of the joint in the contact analysis depends on the defined static friction coefficient μ. The higher coefficient μ, the bigger force we need to deform the joint in its angle plane. Considering the self-locking character of a dovetail joint and our results we can assume that a contact model with friction coefficient of 0.4–0.45 reaches the strength characteristics of a glued joint (non-contact analysis). However, this assumption has to be verified by experimental testing.

The dependence of the bending moment at 2 mm deformation on the static friction coefficient is presented in fig. 5. It shows us that although the contact analysis is a highly non-linear problem, the dependence of the bending moment on the coefficient μ is directly proportional.

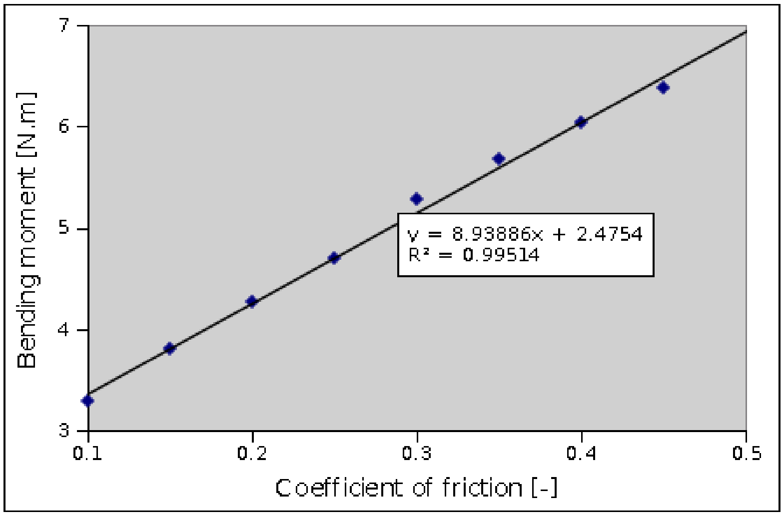

Fig. 5: The dependence of the bending moment on the friction coefficient

The issue of friction is much more complicated in the real environment as it includes the friction occurring during the movement of an object; for this purpose we would have to include the dynamic friction coefficient. This coefficient, which is usually lower than the static coefficient, has not be considered in our simulations because we are dealing with quasistatic loading in which none of the parts of the joint is put to motion before the analysis, i.e. this situation does not require the dynamic friction coefficient.

To get a notion to what extent the reaction forces of the joint can vary in different material models, we conducted further analyses, see Table I.

	Contact – μ = 0.2					Non-contact	
Material	spruce	poplar	ash	oak	plywood	plywood	spruce
F [N]	7.3	9.1	12.9	11.8	23.7	35.1	22.3

Table 1: Maximum reaction forces with various material models

Table I reveals that the reaction force (or the joint stiffness) is highly dependent on the material properties. Because of the high variability of properties of wood, table I serves for the purpose of information valid ad hoc. The highest reaction forces are to be found in the joints from plywood, followed by ash and oak.

Conclusion

The parametrization and finite element analysis of the furniture dovetail joint is the main focus of this paper. Two numerical models were created for this purpose – a contact model and a non-contact model. Both models are fully parametric and have been written in the APDL language. Moreover, the impact of the static friction coefficient on the joint stiffness was examined within the framework of the contact model. The non-contact model served as a reference model for the contact model and also determined its limits of usability.

The results of the contact analysis clearly show that the bending moment, or the stiffness of the joint, is directly proportional to the friction coefficient, as the regression equation in fig. 8 proves. When the friction coefficient is increased from 0.1 to 0.45, the joint stiffness almost doubles. Literary sources conclude that the friction coefficient in the case of wood and wood based products can be between 0.1 and 0.45. It depends on the orientation of the friction surfaces in relation to the orientation of fibres, as well as on the technological operations the material surface was treated by. Moreover, we can assume on the basis of the results that the stiffness of the contact model will approach the upper limit of the empirical interval of the friction coefficient (0.4–0.45). The results of the finite element analyses can be considered correct at this stage, however, really accurate comparisons have to wait until after subsequent experimental verification. Only then can we say to what extent our numerical models are accurate. The partial analysis of the impact of wood species with their material properties on the stiffness of the joint showed that the highest stiffness is achieved when plywood is used, followed by ash, oak, poplar and spruce. The parametric models can be used for the designing of more complex furniture products with higher demands concerning stiffness characteristics (such as furniture for sitting). However, this assumption is dependent on the correction of the created parametric models by experimental testing.

The development and usage of the FEM and CNC tools in the field of furniture design as such, but especially in the industrial design, proves that there are many opportunities, as we are also trying to show in this paper. The FEM analyses and CNC production have been used in purely technical fields, e.g. in electrical technology, engineering or civil engineering, for some time now. However, considering the contribution of the furniture industry for example to the gross domestic product, it seems that FEM together with CNC has a big potential in this field as well.

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