

MECHANICAL PERFORMANCE AND CONTACT ZONE OF TIMBER JOINT WITH OBLIQUE FACES

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Abstract

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The goal of the work was to evaluate mechanical performance of full-scale timber beams containing scarf joint with a dowel. Work focused on standard testing using modular system to obtain effective stiffness and strength of the beams with and without the joint. The work further researched a contact zone between two timber parts of the joint – at the scarf face. This was carried out using non-destructive optical technique – digital image correlation (DIC) and newly developed algorithm. The joint was made of Norway spruce, dims. 6×0.2×0.24 m and was loaded by two modes: a) 3-point bending and b) 4-point bending. During the loading, a sequence of images was acquired for further investigation of contact zone using the proposed algorithm. The joint with scarf and dowel provided enough effective stiffness, i.e. 73–93% for 3-point bending test and 71% for 4-point bending with respect to MOE measured on reference solid beams. Effective strength of the joint was also relatively high and in a range of 55% and 60% with respect to reference solid beams in both 3-point and 4-point bending tests. Contact length differed for loading modes. Mean contact length in symmetrical 4-point bending was about 40%, for asymmetrical 3-point bending test, it was approx. 20% on face closer to support and 44% on a face closer to loads.

Keywords: timber joint, contact zone, bending, digital image correlation, non-destructive testing, dowel

INTRODUCTION

Evaluation of mechanical behavior of timber joints used in historical constructions is of high interest in the Czech Republic. The reasons are a) a high number of historical structures in the area of Czech Republic and 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. For the analyses of such joints one can use experimental, analytical or numerical approach. The analytical approach, especially in the context of dowel-like joints, is mostly based on the Johansen theory (1949) and is incorporated in the standards such as Eurocode 5. Experimental assessment

of timber joints' behavior is a main source of data collection used in research and engineering practice. Currently, it is to a convenience to employ optical-based techniques such as digital image correlation (DIC) that can provide full-field displacements and strains. Not only in historic timber joints but also in other engineering areas DIC has broad range of applications. Historic timber joints is one of the areas where the strengths of the method can be efficiently used. Timber joints are prone to brittle cracking which can lead to damage of the testing equipment.

Area of a place at which two bodies interact – contact zone – is an important geometrical parameter influencing stress/strain transfer and, consequently, behavior of the whole structure. In structural calculations of joints, the contact zone

is often idealized in terms of its size and, moreover, is assumed as time-independent. It was reported in many various disciplines such assumptions reduces the physical behavior of the interaction (Ojolo and Awe, 2011; Kar and Mohanty, 2008; Ivanov and Augsburg, 2008). The same assumptions often underlie analyses of the timber joints used in civil engineering (Li *et al.*, 2009) where, moreover, metal connectors are often used to position the wooden parts while providing efficient load transfer (Branco *et al.*, 2011). In a case metal connectors cannot be used due to inducing brittle-like behavior of joint (Parisi and Piazza, 2000), the contact zone should be of higher interest since parameters such as wood heterogeneity and geometrical imperfections may substantially contribute to lower strength and rigidity (Bodig and Jayne, 1993; Aman *et al.*, 2008).

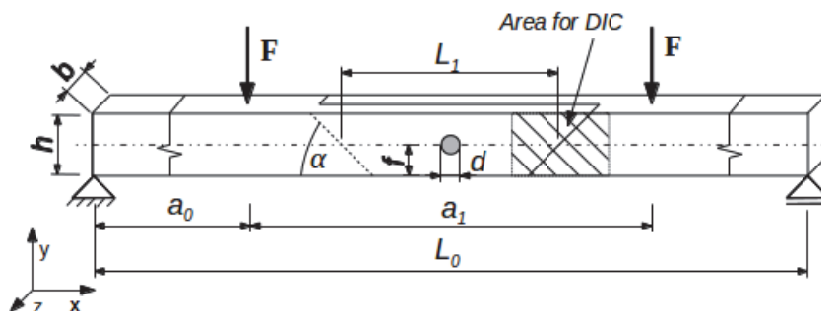
Experimental determination of contact zone in wooden joints has not been paid attention and is mostly missing in literature. There are partial studies reporting influence of loose joints that are special case of reduced contact length (Likos *et al.*, 2012). Principally, the most robust solution for contact zone detection would be to use an X-ray CT scan to record whole loading process of a joint. Subsequent digital volume correlation (DVC) analysis would provide strains in 3D and in time and would give an exact detection of contact zone. Nonetheless, such approach was tested just on laboratory level for 3-point bending test of micro-sample (Forsberg *et al.*, 2008 and 2010) and it is far to be applied on full-scale joints and more frequent use. More practical approach instead is to use optical techniques either working in full-field regime (Muszyński and Launey, 2010; Stemolkas *et al.*, 1997) or point-wise as showed in Schober (2000). The contact zone determination is not the issue in numerical analyses of wooden joints because they standardly use the contact elements that, though, geometrically and physically simplify the contact zones, but allow opening, sliding and closing of contact pair according to the physical situation, so one can learn where parts of the joints came into a contact (Feio *et al.*, 2013; Mackerle, 2003; Jandejsek *et al.*, 2011).

Therefore, to address issues of experimental detection of contact zone in timber scarf joints, we propose a new algorithm based on DIC principle. The specific goals were: 1) to test and measure

mechanical performance of full-scale timber beams with joints subjected to bending; 2) to develop an effective and quick procedure to determine contact zone from optical images.

MATERIALS AND METHODS

For all experimental work real-size wooden beams made of Norway Spruce (*Picea abies* L. Karst) were used. Mean relative moisture content was 19%, the mean density at zero moisture content was 396 kg.m^{-3} (standard deviation is 51.8). All specimens were tested using modular testing equipment that allowed variable experimental setup. The loads in all bending tests were induced using hydraulic inducers GTM series K (max. force 50 kN). In the 3-point bending test the load was located in the beam center, and in the 4-point bending test the loads were in 1/3 and 2/3 of the total beam length (Fig. 1). All bending tests followed ČSN EN 408+A1 (2012) with minor modifications. Deflection at the point of load application and at the beam center was measured using common deflectometers of resolution 0.01 mm, strains at contact zones of oblique faces were measured using digital image correlation (DIC) algorithms, see below for more information. For convenience, all beams were tested upside down, and the beams' self-weights were removed from the calculations. For the 3-point bending, the joint was located 1500 mm from the beam center, the geometry is the same as in Fig. 1. The tested joint was designed to have only two oblique faces and one single pin going through the both parts of the joint. The beam length was 6 m, cross-section was $0.24 \times 0.2 \text{ m}$ (height $\times$ width). The joint length was 1.5 m. The angle of the joint (α) was 63° and the bolt diameter was 40 mm. Altogether 8 beams were tested in 3-point, 4 beams in 4-point bending test and 4 beams were tested without the joint as a reference data set. The dowel was made of common structural steel. During each bending test a sequence of pictures was acquired. For this purpose a Cannon EOS 600D camera of 17 MPix resolution (10 px/mm) was used. Because the loading was quasi-static (300 s to maximal load) the acquisition rate was set up to 1 image per 5 s resulting in 60 images per test. The region of interest (ROI) for subsequent analysis with proposed



1: Geometry of tested beam and joint with scarf in 4-point bending test with joint in the beam center

algorithm was defined at the interface where both parts of the joint come into a contact – oblique face.

The effective modulus in elasticity in 3-point (MOE_T) and 4-point (MOE_F) bending test were calculated following formulas:

$$MOE_T = \frac{Fl^3}{4bh^3y}, \quad MOE_F = \frac{23Fl^3}{108bh^3y},$$

where

F measured load [N],
 l total beam length [m],
 b beam width [m],
 h beam height [m],
 y the deflection [m].

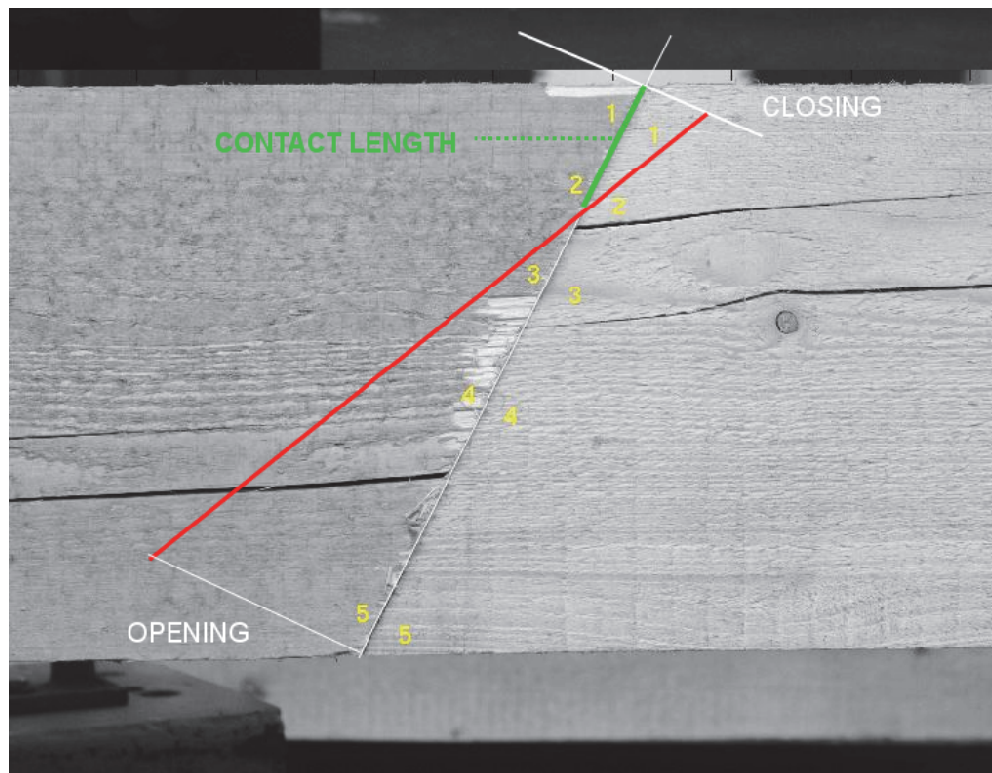
Description of Contact Determination Algorithm

The algorithm can be divided into two parts:
 a) the tracking of the points for which a standard 2D digital image correlation (DIC) algorithm was used (Jandejsek *et al.*, 2011); b) the processing of coordinates of tracked points to determine the contact length. The DIC method is commonly used for investigation of strain distribution over the ROI. However, in the work only five pairs of virtual extensometers (10 points) located at opposite sides of the joint face were used to investigate the mutual contact of the joint faces. The principle of the algorithm is depicted in Fig. 2. The motion of the markers extracted from the image sequence was processed in the second part of the algorithm.

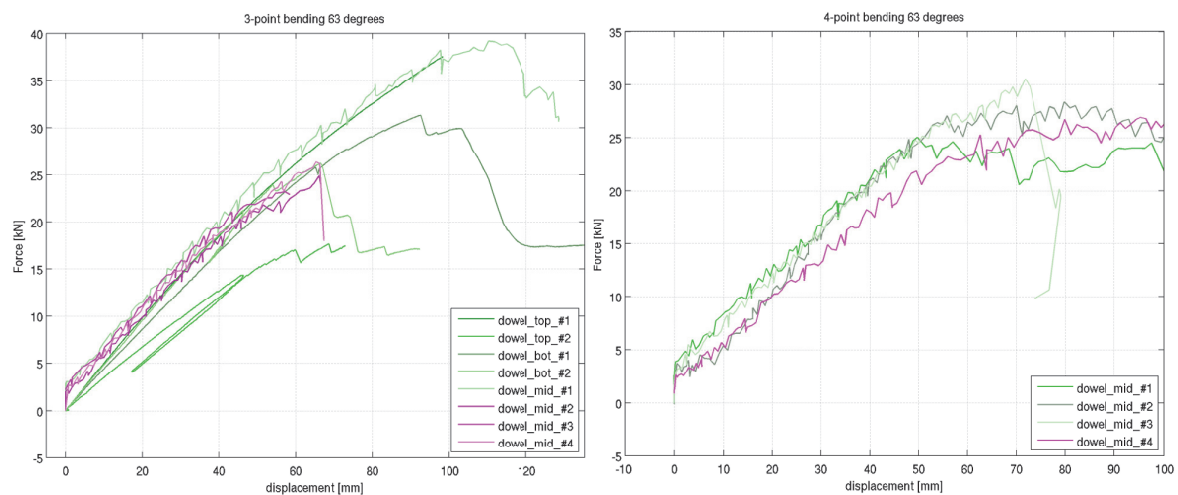
The coordinates of each pair of points were rotated in every step to get them oriented with respect to the Y-axis perpendicular to the face. The distance differences in the rotated Y-axis and X-axis directions represent closing of the contact pair as well as sliding between the two faces respectively. Therefore, both closing/opening and sliding behavior could be extracted from the image data. Once the differences were drawn along the length of the face, interpolation through the given points using a polynomial was carried out to calculate the zero point position. This position represents the length of the mutual contact between joining faces. The contact length was calculated within whole tests' duration, but it is demonstrated at load level of 10 kN, which is common service load level of such beams. The algorithm was implemented in the MATLAB environment (v. 2009).

RESULTS AND DISCUSSION

The force-deflection diagrams revealed the global behavior of the joints (Fig. 3). Fig. 3 indicates that all tested specimens do not exhibit an initial consolidation that is typical for dowel connections and is often illustrated as a nonlinear response of joint in the beginning of the loading process. The specimens were tested upside down joint because of the experimental equipment limitations. Therefore, the very first parts of the curves that are almost vertical express the self-weight of the tested samples – force increases without



2: Principle of the proposed algorithm for contact detection in wooden scarf joints



3: Force-deflection diagrams, left – three-point bending test; right – four-point bending test

the deflection. The fact that after this initial phase the linear elastic behavior started immediately is possible to explain by the near-to-perfect contact between the wooden joint parts and the steel dowel. The linear-elastic phase in both bending modes exhibits almost identical behavior when the dowel is located in the middle of the joint height. In this phase, the curves grow gradually although in a zigzag character. To compute the modulus of elasticity in four-point bending (MOE_F) and three-point bending (MOE_T) the corresponding parts of the curves were interpolated by lines and from these the stiffness was calculated and it is shown in Tab. I.

At the plastic deformation range, the 3-point and the 4-point bending modes differ significantly. The 3-point bending exhibits a relatively short period of plastic response after which the failure of the joint starts to develop. The plastic deformation

of the joint means the local reaching of the wood strength and it usually occurred around the dowel due to its high stiffness. On the contrary, the 4-point bending test shows a relatively long plastic deformation range and created so-called yield plateau, which was recently also reported by Dorn *et al.* (2013). A different plastic responses in both modes of loading may indicate that the combined moment and shear loading is more likely to cause a rapid and brittle failure in the wood beams with joints.

Tab. I reveals the relationship of stiffness in 3-point bending on a dowel vertical position. The highest MOE_T was achieved for the joint with a dowel located in the middle (mean value is 9.33 GPa) and the lowest MOE_T was recorded for joint with dowel at the top position (mean value is 7.36 GPa). The middle value of mean MOE_T was

I: Results from experimental assessment of the wooden joint with oblique faces

Test mode	Dowel position	Sample No. [#]	MOE_T [GPa] (mean)	MOE_F [GPa] (mean)	Fmax [kN] (mean)
3-point bending	Bottom	1b	8.04 (8.58)	-	31.0 (28.6)
		2b	9.12	-	26.2
	Middle	3m	10.17 (9.33)	-	35.4 (28.15)
		4m	8.69	-	22.9
		5m	9.27	-	21.0
		6m	9.20	-	23.7
	Top	7t	8.58 (7.36)	-	37.6 (27.3)
		8t	6.13	-	17.0
4-point bending	Middle	9m	-	8.95 (8.40)	22.4 (24.9)
		10m	-	8.69	25.4
		11m	-	8.66	27.8
		12m	-	7.31	24.0
Reference solid beam	3-point	13r	8.79	-	19.1 (46.7)
		14r	11.23	-	46.7
	4-point	15s	-	11.31 (11.73)	43.1 (45.7)
		16s	-	12.15	47.5

II: Mean contact length achieved for the 3-point and 4-point bending tests; in brackets: standard deviation in [%]

	Face	No. of samples	Mean contact length (std. dev.) at 10 kN in [%]
3-point bending (asym.)	1	2	43.8 (14.7)
	2	2	19.9 (4.5)
4-point bending (sym.)	1 = 2	4	30.7 (13.1)

achieved when the dowel was in the bottom position (8.58 GPa). The sample 8t exhibited an extreme value of MOE_T (6.13 GPa), which can be attributed to high number of inherent faults in wood such as knots and drying cracks. In the 4-point bending tests, the mean experimental MOE_F was 8.40 GPa, which gives approx. 28% reduction with respect to mean MOE_F of the reference beams.

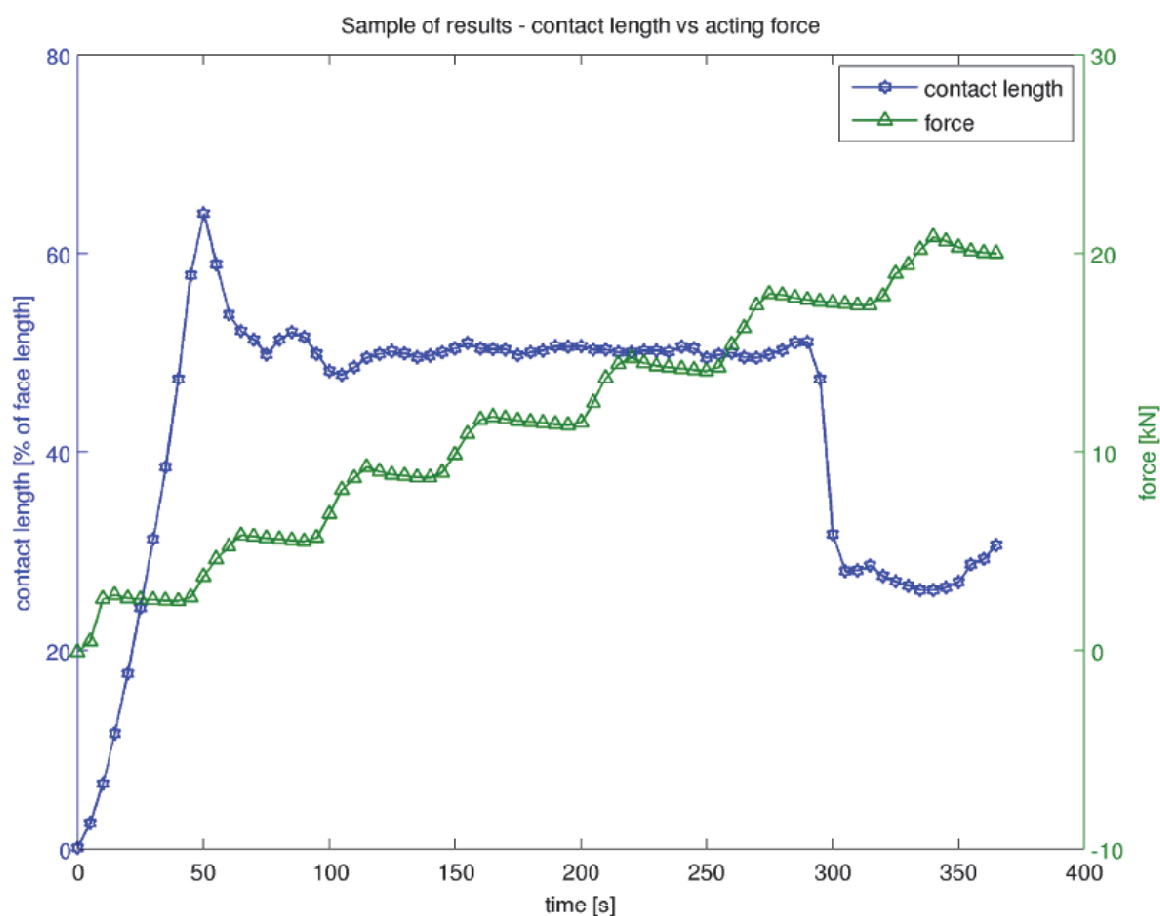
In terms of maximal load (F_{max}) in the 3-point bending test, the influence of the dowel position is less interpretable because of both a significant variance of maximal force ranging from 17 to 37.6 kN and because the corresponding numerical study that could support the findings was not conducted. Nonetheless, the results (Tab. I) indicate that the dowel vertical position does not have such an influence on F_{max} as on MOE . Rather, the maximal load is impacted by geometrical intolerances and wood properties, especially in direction perpendicular to grain. The reason is that the most of the tested joints failed at the oblique faces in that direction. In the 4-point bending tests the mean value of maximum load was 24.9 kN, slightly lower than the mean in the 3-point bending tests which resulted in 28.02 kN. This gives the positive message since in real structures the joints are rarely loaded only in pure bending mode, but more often it is loaded by combined bending and shear. The correlations between F_{max} and MOE are very low for both bending modes. For the 3-point bending test the Pearson correlation coefficient is 0.43 and for the 4-point bending it is 0.1. Therefore, the prediction of the strength from the stiffness is rather low and, again, it reveals how much the wood is heterogeneous and variable at such large scale of specimens.

The result of the contact length analysis is showed in Tab. II. It indicates that for 3-point bending test there is different behavior on both faces of the joint (43.8% vs. 19.9%). Despite the fact, there are not many specimens measured due to their sizes, it indicates that both faces of the joint are loaded by different conditions (asymmetrically). This is often the case in real constructions. If we also consider the imperfections in joint geometry that are commonly present in real constructions due to their *in situ* manufacture, the load transfers are very various and may lead to deformation on very local areas (20% of length). The symmetric

setup in 4-point bending is not comparable to the results of 3-point bending and represent more ideal conditions. Even here we see that mean contact length is about 31%.

Although we do not compare the groups, both results are advantageous and can be used in structural analytic calculation of trusses. Nevertheless, in the group of 4-point bending there can be seen also very high standard deviation even though number of samples is twice higher than for 3-point bending. This behavior is commonly obtained in measurement of organic and heterogeneous materials as wood. Thus, higher standard deviation in determination of contact length does not invalidate the results. The result emphasizes the importance of such algorithm in timber joints' analyses for more precise quantification of contact phenomena that can include also sliding. The contact length varies substantially with the change of load as seen in Fig. 4.

For the purpose of a structural analysis it is important to set well the acting force/bending moment level at which the contact length should be read. This task is crucial and should be made with regard to the loads present in the designed structure. The algorithm has a few features which should be discussed. First, before the faces come into contact the results are questionable because the objects are free to move and the values obtained from the zero finding procedure can be extreme. Second, although the contact length is known, the stress distribution over the contact area is not known due to the fact that all DIC measurement is only at the surface and may substantially vary within the beam thickness. However, for the timber joint research it is not as important and an assumption of uniform distribution of loads spread over the contact length can be accepted. Another problem connected to the acquisition of contact length is the need of synchronization of the camera and the driver which measures the quantities (forces, displacements). This issue is critical because standard cameras have minimum delay between the acquisition of pictures about three seconds, which may invalidate the results. This problem can be solved using small number of cycles with very small load in the beginning of the measurement which produces enough data for later synchronization.



4: Contact length at oblique face in a course of time and related to force

CONCLUSION

Within the work, the full-size timber joints were measured in terms of their effective stiffness and strength and further examined using digital image correlation (DIC) to investigate contact length of the joint on its oblique face. The joint with oblique faces and dowel provided enough effective stiffness, i.e. 73–93% for 3-point bending test and 71% for 4-point bending with respect to MOE measured on reference solid beams. Effective strength of the joint was also relatively high in a range of 55% and 60% with respect to reference solid beam for both 3-point and 4-point bending tests, respectively. Effect of the vertical position of a dowel was also proved for 3-point bending test, the highest MOE was obtained when dowel was in a neutral axis of beam, the lowest in a top of beam cross-section. An investigation of contact length that is important parameter for structural design of beams and joints was carried out using new algorithm based on digital image correlation. The proposed algorithm is efficient and provides quick information about the contact length from images. Moreover, the proposed technique is partially able to take into a consideration also the third dimension of the contact zone that is not visible for the camera, e.g. although in 2D there is only a gap between the two interfaces visible, if there is contact present in the non-visible depth, the surface points do not move either. Thus, the algorithm is able to recognize this issue without precise quantification in 3D. Mean contact length in symmetrical 4-point bending was about 31%, for asymmetrical 3-point bending test, it was approx. 20% on face closer to support and 44% on a face closer to loads.

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REFERENCES

- AMAN, R. L., WEST, H. A., CORMIER, D. R. 2008. An evaluation of loose tenon joint strength. *Forest products journal*, 58(3): 61–64.
- BODIG, J., JAYNE, B. A. 1993. *Mechanics of wood and wood composites*. Krieger Pub, New York.
- BRANCO, J. M., PIAZZA, M., CRUZ, P. J. S. 2011. Experimental evaluation of different strengthening techniques of traditional timber connections. *Engineering Structures*, 33: 2259–2270.
- CZECH OFFICE FOR STANDARDS, METROLOGY AND TESTING. 2012. *Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties*. ČSN EN 408.
- DORN, M., DE BORST, K., EBERHARDSTEINER, J. 2013. Experiments on dowel-type timber connections. *Engineering Structures*, 47: 67–80.
- FEIO, A. O., LOURENC, P. B., MACHADO, J. S. 2013. Testing and modeling of a traditional timber mortise and tenon joint. *Materials and structures*. DOI 10.1617/s11527-013-0056-y.
- FORSBERG, F., MOOSER, R., ARNOLD, M., HACK, E., WYSS, P. 2008. 3D micro-scale deformations of wood in bending: synchrotron radiation μ CT data analyzed with digital volume correlation. *J. Struct. Biol.*, 164(3): 255–262.
- FORSBERG, F., SJÖDAHL, M., MOOSER, R., HACK, E., WYSS, P. 2010. Full Three-Dimensional Strain Measurements on Wood Exposed to Three-Point Bending: Analysis by Use of Digital Volume Correlation Applied to Synchrotron Radiation Micro-Computed Tomography Image Data. *Strain*, 46(1): 47–60.
- IVANOV, V., AUGSBURG, K. 2008. Assessment of Tire Contact Properties by Nondestructive Analysis. Part I. The Contact Length in the Region of Adhesion at Slow Rolling Velocities. *Journal of Friction and Wear*, 29(5): 362–368.
- JANDEJSEK, I., NACHTRAB, F., UHLMANN, N., VAVŘÍK, D. 2011. X-ray dynamic defectoscopy utilizing digital image correlation. *Nuclear instruments & methods in physics research section A-accelerators spectrometers detectors and associated equipment*. 11th International Workshop on Radiation Imaging Detectors, 633(1): 185–186.
- JOHANSEN, K. W. 1949. Theory of timber connections. *International Association of Bridge and Structural Engineering Publications*, 9: 249–62.
- KAR, C., MOHANTY, A. R. 2008. Determination of time-varying contact length, friction force, torque and forces at the bearings in a helical gear system. *Journal of Sound and Vibration*, 309(1–2): 307–319.
- KUNECKÝ, J., SEBERA, V., TIPPNER, J., ARCISZEWSKA-KEDZIOR, A., HASNÍKOVÁ, H., KLOIBER, M. 2014. Experimental assessment of historical full-scale timber joint accompanied by a finite element analysis and digital image correlation. *Construction and Building Materials*, in press.
- LI, Y. F., TSAI, M. J., LIAO, C. N., TSAI, J. H. 2009. Effects of Tenon Depths and Bolt Constraint Conditions on the Mechanical Behavior of Semi-rigid Joints of Wooden Historical Buildings. *Advances in structural engineering*, 12(3): 349–358.
- LIKOS, E., HAVIAŘOVA, E., ECKELMAN, C. A., ERDIL, Y. Z., OZCIFCI, A. 2012. Effect of tenon geometry, grain orientation, and shoulder on bending moment capacity and moment rotation characteristics of mortise and tenon joints. *Wood and Fiber Science*, 44(4): 462–469.
- MACKERLE, J. 2003. Finite element analysis of fastening and joining: A bibliography (1990–2002), *International Journal of Pressure Vessels and Piping*, 80: 253–271.
- MUSZYŃSKI, L., LAUNEY, M. E. 2010. Advanced imaging techniques in wood-based panels research. In: THOEMEN, H., IRLE, M., SERNEK, M. (eds.), *Wood-Based Panels – An Introduction for Specialists*. Brunel University Press, 177–201.
- OJOLO, S. J., AWE, O. 2011. Investigation into the Effect of Tool-Chip Contact Length on Cutting Stability. *Journal of Emerging Trends in Engineering and Applied Sciences*, 2(4): 626–630.
- PARISI, M. A., PIAZZA, M. 2000. Mechanics of plain and retro_tted traditional timber connections. *Journal of Structural Engineering*, 126(12): 1395–1403.
- STEMOLKAS, J. W., ZINK A. G., LOFERSKI, J. R. 1997. Image correlation analysis of multiple-bolt wood connections. *Wood and Fiber Science*, 29(3): 210–227.
- SCHÖBER, K. U. 2000. Numerical simulation of contact problems – traditional timber joints under monotonous loading. Universität Dortmund. 13.

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