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ASSESSMENT OF MECHANICAL BEHAVIOR OF HISTORIC TIMBER JOINTS PERFORMED USING DIGITAL IMAGE CORRELATION

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Abstract. *Because traditional historic timber joints lack standardized design rules, their testing is of high importance. For a detailed analytical model it is needed to know where and when the parts of the joint come into contact during the loading of the structure. To measure this quantity it is possible to use extensometers, however, because of presence of big displacements and brittle cracking it is preferable to introduce more efficient tool, the digital image correlation (DIC) method. In the work DIC was applied in experimental analysis of a joint. The joint is intended for replacement of decayed parts of ceiling joists and consists of two oblique faces and a single pin in the middle of the faces. The joint was made in a beam (Norway spruce, dims. 6x0.2x0.24 m, number of samples N=8) in two positions: four joints (group A) were loaded using both shear and bending moment loading (1.5 m from the support, three point bending), four joints (group B) were loaded using bending moment (in the middle between applied forces, four point bending). During the loading a camera triggered by a remote camera controller took pictures every five seconds. The algorithm used in this study is more deeply described in the article.*
The results show the group A has different contact length on both sides which was caused by different loading at the two ends (face length μ=43.8%, σ=14.7% vs. μ=19.9%, σ=4.5%). In the group B where the contact length should be equal the obtained standard deviation of the contact length determination was μ=30.7%, σ=13.1%. Not only the contact length, but also sliding behavior of the two surfaces can be described this way. It is an efficient and simple way suited especially for investigation of timber connections and can be directly applied to analytic models of the joint.

1 INTRODUCTION

Not only in historic timber joints but also in other engineering areas has digital image correlation broad range of application. 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. The efficacy of the method lies also in the ease of whole the procedure: only tripod and a quality camera is needed. Area of a place at which two bodies interact between each other - 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 [1], [2], [3]. The same assumptions often underlie analyses of the wooden joints used in civil engineering [4] where, moreover, metal connectors are often used to position the wooden parts while providing efficient load transfer [5].

In a case metal connectors cannot be used due to inducing brittle-like behavior of joint [6], the contact zone should be of higher interest since parameters such as wood heterogeneity [7] and geometrical imperfections may substantially contribute to lower strength and rigidity [8].

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 [9]. 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 [10], [11] 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 [12], [13] or point-wise as showed in [14]. 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 [15], [16]. Therefore, to address issues of experimental detection of contact zone in historical scarf joints, we propose a new optical-based technique. The specific goals were: 1) to develop an effective and quick procedure to determine contact zone from optical images; 2) to apply developed technique on full-scale historical scarf joints subjected to bending.

2 MATERIALS AND METHODS

The tested joint was designed to have only two oblique faces and one single pin going through the both parts of the joint, see Figure 1. The beam length was 6m, cross-section was 0.24x0.2 m (height x width). The joint length was 1.5 m.

The angle of the joint (α) was 63° and the bolt diameter was 40 mm. For all tests the Norway spruce (*Picea abies L.*) timber was used. Altogether eight beams were tested, four in 3-point and four in 4-point bending test. 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 (150 s to maximal load) the acquisition rate was set up to 1 image per

5 s resulting in 30 images per test. The region of interest (ROI) for subsequent analysis with proposed algorithm was the one where the two interfaces come into contact.

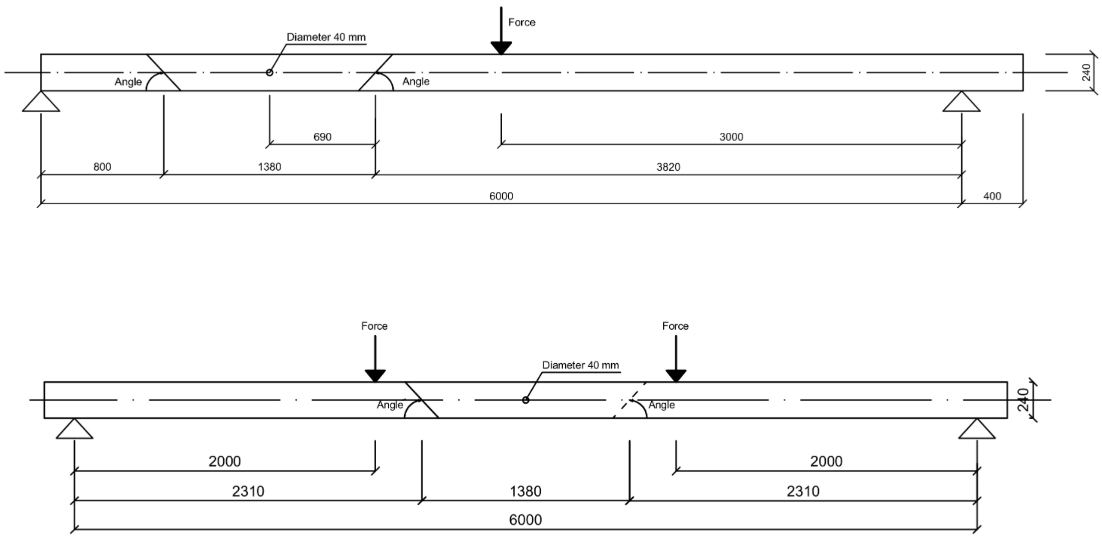

Figure 1: Joint from the group A (top), group B (lower).

2.1 Algorithm description

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 [17]; b) processing tracked points' coordinates to determine the contact length. The DIC method is commonly used for investigation of strain distribution over the ROI. However, in the work only ten points (five pairs) located at opposite sides of the joint face were tracked to investigate their mutual contact. The structure was considered to be rigid and the deformation was not taken into account. The motion of the markers extracted from the sequence was processed in the second part of the algorithm. The coordinates of each pair of points were rotated in every step to point by the y-axis the same direction. The distance differences in the rotated y-axis and x-axis directions represent closing of the contact pair and the sliding between the two faces respectively. Therefore, both closing/opening and sliding behavior is known. Once the differences were drawn along the length of the face, interpolation through the given points using a polynomial was performed to calculate the zero point position which represents the length of the contact. The algorithm was implemented in the MATLAB environment.

3 RESULTS AND DISCUSSION

The result (see Table 1) shows in group A different behavior of both faces of the joint (43.8% vs. 19.9%). It is caused by different loading conditions on both faces. The symmetric setup in 4-point bending (group B) is not comparable to the results of group A due to the different loading.

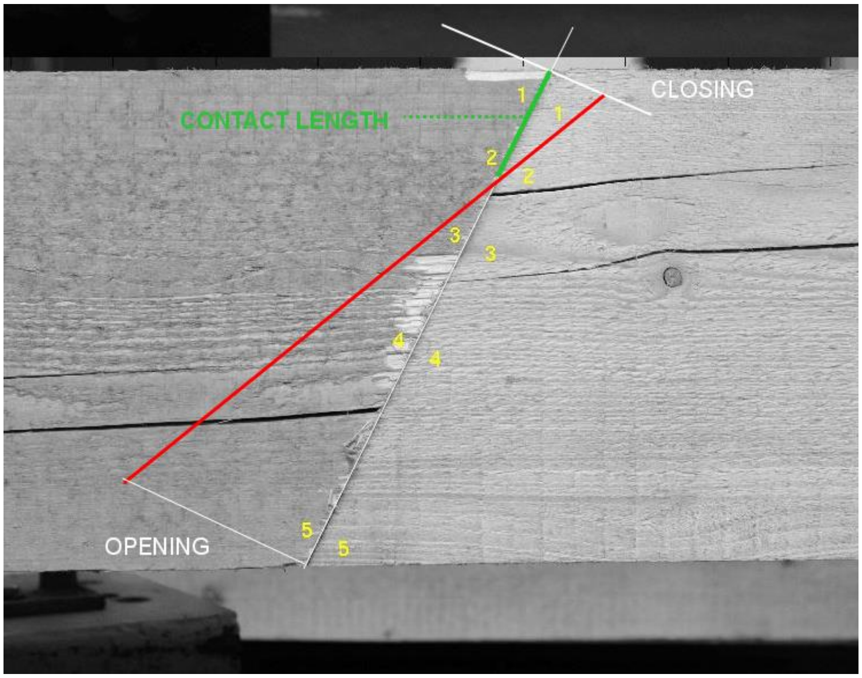

Figure 2: Principle of the algorithm.

Although we do not compare the groups, both results are advantageous for an analytic model of the joint. Nevertheless, in the group B there can be seen also very high standard deviation although number of samples is two times higher than in A. This behavior is commonly obtained in measurement of organic materials. 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. For the purpose of a static 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 very unreliable 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. 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. The algorithm is efficient and provides quick information about the contact length. Moreover, the proposed technique is partially able to take into 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. The same can be stated when the joint is subjected to buckling (out-of-plane bending). 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 pictures about three seconds, which can invalidate the results. This 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.

Another interesting output of the analysis is the description of the sliding behavior of the faces. Above only algorithm based on the smallest distance between the points was described, nevertheless, if the points are well placed on the surface (perpendicularly to the cut), the respective movement in the direction of the cut can be plotted and used for analysis of the friction influence or, more often, for the assessment of the onset of cracking in the direction perpendicular to the grain.

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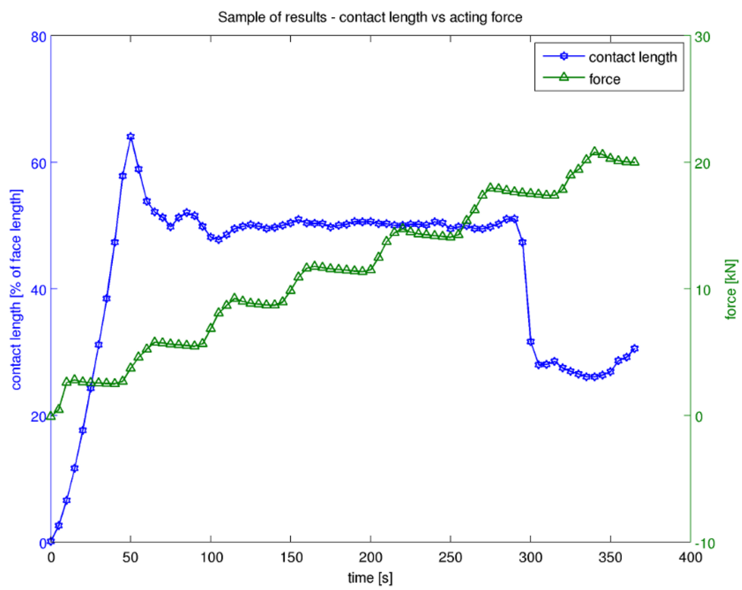

Figure 3. Contact length and acting load in time.

Table 1: 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)

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