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# Experimental testing and theoretical prediction of traditional dowel-type connections in tension parallel to grain

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ABSTRACT

This paper presents theoretical and experimental assessment of full-scale traditional dowel-type connections in tension parallel to grain made of Norway spruce (*Picea abies* L. Karst.) and English oak (*Quercus robur* L.). The joint dimensions were derived from the nominal dowel diameter $d = \{12, 16, 20, 24\}$ mm according to the European standards EN 383 and EN 26891. Determination of the total joints displacement and surface strain distribution on the dowels was carried out using digital image correlation (DIC) technique. The theoretical and experimental approaches were focused on the determination of the load-slip joints moduli ($K$) and the dowel load-carrying capacity ($P_y$) for various dowel diameters with the same length/diameter ratio equal to 3. The theoretical solution of the load-slip joints stiffness was carried out according to the Beam on Elastic Foundation (BEF) theory and the dowel load-carrying capacity according to Johansen's yield theory based on the European yield model (EYM). The theoretical results correlated with experimental values quite well. The theoretical solution proved to be a proper way for the design of the wooden dowel-type joints from the safety perspectives.



## 1. Introduction

The traditional all-wooden joints play an important role in the structural behavior of historical timber structures. Their connections are usually the handicrafts that testify to the high carpentry skills and knowledges of the overall mechanical behavior of the timber structure, which are based on experience and long-term experimental testing [1,2]. These connections are commonly referred as the most critical element in structures, being responsible for the reduction of the overall integrity in 80% of failure cases [3–5].

Within historical timber structures traditional carpentry joints were used while wooden dowel fixed mutual position of elements. The wooden dowel mechanical behavior is important for appropriate structural and geometrical designs [6]. The geometrical parameters of the fastener, mainly diameter and slenderness ratio, influenced the total mechanical joints performance [7]. The fastener with a low slenderness ratio remains more or less unbend during joint loading, thus the total joint failure will be caused by exceeding of the load-carrying capacity of connected elements. The related failure mode in this case is "brittle". On the other hand, the fastener with a high slenderness ratio is deformed in bending, which reduced a splitting tendency of the joint components. Thus, the total joint failure will be caused by exceeding of load-carrying capacity of fastener itself. However, the bending fastener deformation is limited by the embedment strength of the joint components in the contact zone between fastener and joint components [8,9]. Therefore, the ductile failure mode can be expected [10,11].

In the past, many studies about this issue have been performed (such as [12,13]). Johansen [12] proposed the first mathematical model (European yield model – EYM) for joints strength performance. He applied the model for timber-to-timber connection with a steel dowel for ductile failure modes. Larsen [14] continued and developed Johansen's theory further. The validity of this method was confirmed by experimental investigations by Möller [15]. Brungraber [16] was one of the first who performed the experimental tests on individual wooden joints with traditional fasteners - dowels. These joints were tested in the full-scale dimensions for the purpose of detecting local possible failures.

Recently, a new interest has been paid in all-wooden constructions for the purpose of authentic repairs of cultural heritage sites. Mechanical behavior of the wooden dowels is not precisely known

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and information about stiffness and bearing capacity is rather scarce [17]. Unfortunately, this fact is further supported by the absence of adequate methodology for their design and manufacture. However, in the last years there are some studies, which are clearly focused on assessment of wooden dowels behavior and their performance, e.g. [28,29].

The purpose of this study was to investigate the mechanical properties of single shear dowel-type joints with its detailed performance description where various dowel diameters were used.

The aim of this study was to describe the mechanical performance of full-scale single shear dowel-type joints used in reconstructions of historical timber structures. The main objectives were: (1) to determine the joints slip moduli ($K_{cal}$ and $K_{exp}$) and dowel connection load-carrying capacity with determination of the maximal dowel loading in bending and shear deformation modes ($P_{y,EYM,cal}$, $P_{max,exp}$, $P_{y,S,cal}$ and $P_{failure,S,exp}$) with help of theoretical and experimental approaches, (2) to assess the detailed mechanical dowel behavior through experimental investigation, and (3) to perform a strain analysis of the dowel using digital image correlation (DIC).

## 2. Materials and methods

### 2.1. Material and experimental analysis

The joints components were cut from Norway spruce (*Picea abies* L. Karst.), while its length coincided with the longitudinal direction and a grain angle of 45° on the cross-section was ensured based on practical experience, that this angle is most common for wooden beams in the constructions (see in Fig. 1). The specimens of joints were assembled by components with similar density ($\rho_{12}$) at equilibrium state 12 ± 2% (specified in Table 1). English oak (*Quercus robur* L.) was used to make the dowel (average density 718 kg·m$^{-3}$). Selected wood species represent the most common materials used in reconstructions of historical timber structures in central Europe. The dowels with four nominal diameters ($d$ = {12, 16, 20, 24} mm) were tested. The same dimensions were used to bore the holes in the joint components. The dowels were inserted into predrilled holes using a hammer by gentle tapping to disallow the pre-stressing of the area around the dowel. No clearances were allowed.

The mechanical investigations of the full-scale joints (Fig. 1) were carried out according to standards [22,23]. The joints were loaded in tension parallel to grain in single shear plane. The quasi-static loading rate was 1.5 mm·min$^{-1}$ for all tests. First, the specimen was loaded until 40% of the maximum load ($P_{max,pre}$), which was estimated for each series based on preliminary test, and the crosshead position was held for 30 s. After this step, each specimen was unloaded to 10% of $P_{max,pre}$ and the crosshead position was held for 30 s again. Finally, the specimen was loaded until failure. Fig. 1 and Table 1 present the joints test configurations including the geometric parameters which were derived from the diameter ($d$) according to [25]. The $a_{3,t}$ was determined according to minimal distance between dowel axis and loaded element end, which is specified in Eurocode 5. The parameter $l_2$ was determined based on the preliminary study examining the strain distribution along the specimen width with increasing distances from the clamping ends. The desired uniform strain distribution was observed in distance equal to 6-times dowel diameter. Parameters $b$ and $l_1$ were limited by maximum width and depth of clamping jaws of testing machine. The joints were placed into a climate chamber and conditioned at 20 °C and 65% relative humidity (RH) until the equilibrium moisture content (EMC) was reached. Moisture content (MC) and $\rho_{12}$ were measured gravimetrically according to [21].

The mechanical tests were performed using universal testing machine Zwick Z050/TH 3A (Zwick Roell AG, Germany) with 50 kN load cell under crosshead displacement control.

### 2.2. Digital image correlation

The optical system was used for two purposes: firstly, for the determination of global mutual displacement of connected elements by virtual extensometer (see detail in Fig. 1); and secondly, to obtain the strain distribution on the dowel forehead. The optical measurement of the mutual global displacement between the connected elements allowed the reducing of the observed rigid motion of joints. This phenomenon can be justified by slip of the timber elements in the metal clamping wedges together with the lateral compression of clamping volume resulting displacement of metal clamping wedges in jaws. It should be of concern when loading in tensile mode. The full-field optical system is based on digital image correlation (DIC) and consists of two CCD cameras (AVT Stingray Copper F-504B, Allied Vision Technologies, cell size of 3.45 µm and resolution of 2452 × 2056 pixels) equipped with lenses (Pentax C2514-M, Pentax Precision Co., Ltd., focal length of 25 mm) at the stereo-vision configuration (see in Fig. 1). The patterned samples' surface was illuminated by two light sources

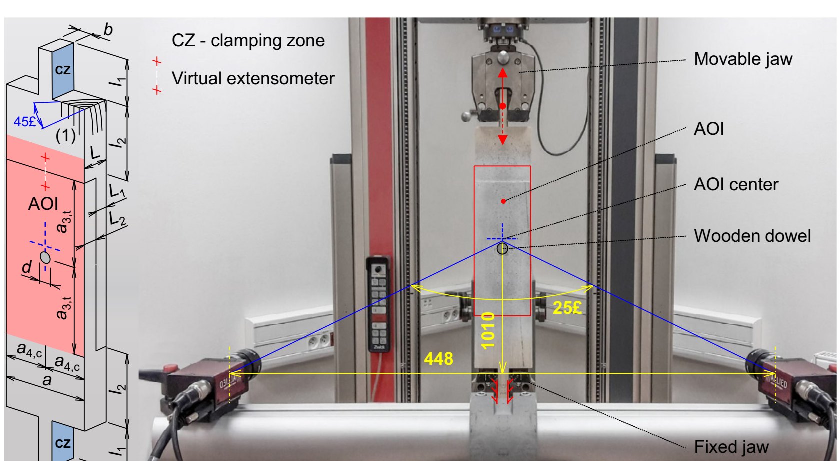


**Fig. 1.** Experimental test configurations: joints geometrical parameters (left); stereo-vision optical system (3D) for image acquisition of the tests (right), dimensions in mm; (1) represents the grain direction.