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Development of the multiple tenon timber connection based on experimental studies and FE simulation

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ABSTRACT

This paper describes the development of the multiple tenon connection from the basic idea to an optimised timber connection. Based on the promising results of a first series of experimental testing, a finite element model considering different failure modes was developed to simulate the load-bearing behaviour of a four-tenon connection. The shape of the multiple tenons and the geometrical position was studied to compare the varying ultimate loads depending on different geometrical parameters. Based on these relations, a second experimental series was developed with an improved design. The results show significantly higher load capacities compared to the results of the first test series. Different possibilities of additional reinforcement have been studied. In comparison to existing form-fitting connections, multiple tenons exhibit a remarkable increase of load-bearing capacity together with reduced scattering of test results. Two-dimensional finite element simulations supported the design optimisation of wood-to-wood connections in a very efficient way.

1. Introduction

Timber-to-timber connections have long traditions in many countries worldwide. Various types have been created by carpenters to connect different parts of a structure without additional connectors. The increasing wages for workers and the decreasing costs of steel parts brought industrial manufactured steel parts for timber constructions onto the market only in the 20th century. Intensive research and development of dowel-type fasteners, in particular screwed connections, led to standardised solutions and a disappearance of the form-fitting timber-to-timber connections in the past few decades.

Innovations of the production and material technologies have changed the thinking about timber connections in the last few years. On the one hand, the development of computerized-numerical-controlled-based (CNC) technologies brought about the innovations for joinery machines which can cut and shape wooden components very precisely in just one operation. On the other hand, the development of homogeneous and high strength materials (e.g. beech laminated veneer lumber (LVL)) demands new types of timber connections.

Several advantages can be assigned to form-fitting connections: the assembly processes could be simplified when the position of the connection is clearly defined by the CNC-machined geometry of the two end parts. Furthermore, innovative joint technology is economic as it saves assembly time. The omission of steel can increase fire resistance. Numerical connection of industrial process like design, manufacturing and logistics will support the machine-fabricated timber joints even more in the future.

Selected – and mainly traditional – timber-to-timber connections have been studied previously. Mortise and tenon joints laterally loaded where mainly investigated by Schelling and Hinkes [1,2] in the 1980s. Studies on rotational or tension loaded traditional pegged mortise and timber joints was carved out by Shanks and Walker [3] as well as Judd et al. [4] regarding different materials and joint geometries. Timber connections under pressure perpendicular to the grain were investigated by Blass and Görlacher [5]. The dovetail connection improved the assembly conditions and the pull-out resistance of the traditional mortise and tenon connection which was investigated by Tannert [6]. Currently, EC5/NA [8] regulations for tenons consider the notched beam related to formulations based on fracture mechanics derived by Gustafsson [9]. Load-bearing capacity and the stiffness values for new types of connections were studied specifically by Enders-Comberg [10] and Rebstock [11]. The aim of the investigations, which are described in the following sections, was to improve the load-bearing capacity of the tenon connection to highlight the performance of form-fitting timber-to-timber connections. Therefore, experimental and numerical studies have been combined in a very efficient way.

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2. Preliminary experimental studies on multiple tenon connections

2.1. Predesign and geometrical considerations

Mortise and tenon connections belong to the family of traditional carpentry joints. The load will be transferred mainly vertical. Mortise and tenon joints are included in the German National Annex to EC5/NA [8]. The design approach is based on the definition for the notched beam and limits the shear resistance of the remaining cross-section by Eq. (1) in combination with the reduction factor, k_v, to prevent tension failure at the bottom corner of the tenon. The resistance against pressure perpendicular to the grain at the bottom of the tenon is limited by Eq. (1). The mortise strength can be calculated following the design proposals for tensile strength resistance perpendicular to the grain with Eq. (1). Shear strength $f_{v,k}$, compression strength $f_{c,90,k}$ and tension strength perpendicular to the grain $f_{t,90,k}$ are decisive parameters for different failure modes.

$$F_{Rk} = \min\begin{cases} \frac{2}{3}b_{ef}\cdot h_e\cdot k_z\cdot k_v\cdot f_{v,k} \text{ (a)} \\ 1.7\cdot b\cdot l_z\cdot f_{c,90k} \text{ (b)} \\ \left(6,5+\frac{18\cdot a^2}{h^2}\right)\cdot(t_{ef}\cdot h)^{0.8}\cdot f_{t,90,k} \text{ (c)} \end{cases} \quad (1)$$

$$k_v = \min\begin{cases} 1 \\ \frac{k_n}{\sqrt{h}\left(\sqrt{\alpha\cdot(1-\alpha)}+0.8\cdot\frac{x}{h}\cdot\sqrt{\frac{1}{\alpha}-\alpha^2}\right)} \end{cases} \quad (2)$$

$$k_z = \beta\cdot(1+2\cdot(1-\beta)^2)\cdot(2-\alpha) \quad (3)$$

Fig. 1 shows the geometrical parameters of a mortise and tenon joint. Tenon Geometry is defined by α and β as a share of the beam height h and the tenon height h_z. The distance of load application x is assumed to be the half of the tenon length l_z. Tenon length influences the notch length in the main beam t_{ef}. The effective tenon width b_{ef} considers possible cracks at the end grain of the beam by k_{cr}. Strength of the main beam is decisively depending on the partial volume under the mortise represented by height a. Value k_n is a material constant and varies between 4.5 for laminated veneer lumber (LVL) and 6.5 for glued laminated timber (GLT).

Regarding a beam-to-beam connection with the same height h, it can be expected that the connection fails mainly due to crack development at the bottom of the tenon or mortise. The decisive parameters are the height h_e and the distance a. These values are interdependent. Consequently, the load capacity is limited by geometrical conditions.

The basic idea of the multiple tenon connection is to keep the contact area constant and reduce the tenon height and length to have two or more tenons with the same cross-section in total. Hence, the cut-out from the supporting beam is reduced considerably due to the reduced length of the multiple tenons.

Fig. 2 shows different configurations of multiple tenons. All

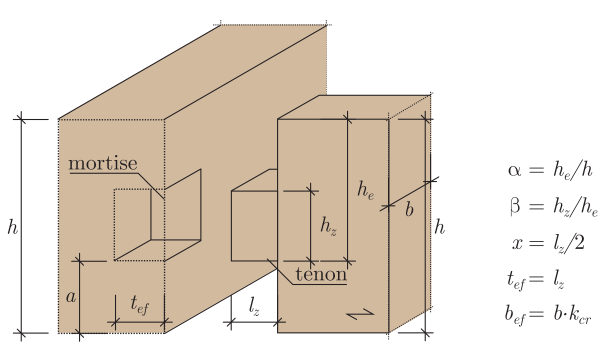

Fig. 1. Geometrical parameters of a mortise and tenon joint with reference to EC5/NA [4].

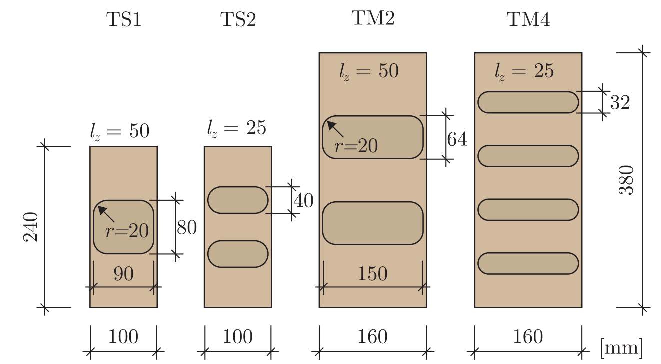

Fig. 2. Tenon configuration of the test specimens of the first experimental series.

processing was carried out by a Hundegger K2, thus, the edges of the mortises and tenons were rounded by a cutting head.

The specimens, TS, were made of solid timber beams of strength class C24 according to EN 338 [12], each with the dimension of 100 mm × 240 mm. A larger beam size of 160 mm × 380 mm made of glued laminated timber (GLT) of strength class GL24h according to EN 14080 [13] was chosen. The beam height of the TM series allows for two or four tenons with a length of 50 mm and 25 mm, respectively (see Fig. 2). See Table 1 for the strength class and density of the solid timber and GLT. One or two self-tapping screws might additionally be used to avoid pull out of the tenons.

2.2. Test set-up

Four series with five specimens each were manufactured on a commercial CNC machine and tested for a basic understanding of strength and deformation characteristics of multiple tenon joints. A shear loaded beam to beam connection was chosen to simulate realistic conditions following the test set-up used by Tannert [6]. The position of tenon and mortise was chosen arbitrary regardless of wooden defects. The single load, V_2, was applied in the middle of the beam under deformation control of 0.5 mm/s (see Fig. 3). The tests were performed according to EN 26891 [14] for timber connections. A distance of $2{\cdot}h$ between the load application point and the tenon joint was chosen to minimise the influence of the discontinuous stress areas. A statically determinate system was created due to the pivot bearings of all three supports. The parameters of the test-setup are shown in Fig. 3.

The force and the deflection of the beam at the load application point were recorded. Moreover, the relative deformation, Δw_1, between the secondary beam and the main beam, and the crack opening beneath the tenons and mortises were measured with displacement transducers.

2.3. Test results

Fig. 4 shows the maximum shear forces, $V_{1,ult}$, of each test specimen and the mean value of each series. Mean values are also documented in Table 1, together with the coefficient of variation (CV). The shear force is calculated as $0.5{\cdot}V_2$. The specimens fail due to tension failure perpendicular to the grain, which started at the lower edge of the tenon at the end grain surface.

The single tenon, TS1, reaches an average capacity of 13.8 kN with a CV of 0.2. The double tenon connection, TS2, shows a little higher resistance of 16.7 kN with a higher spreading of the single failure loads. The cross-sections of series TM2 made of GLT achieve much higher loads with lower spreading. TM2 reaches an average capacity of 52.1 kN and TM4 with four tenons fails at 69.4 kN. This is about 30% higher than series TM2 with only two tenons.

The shear force, V_1, is documented against the deflection of the secondary beam in the centre, $w_{2,o}$, for specimens of series TS1 and TS2