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Assessment of the failure behaviour and reliability of timber connections with multiple dowel-type fasteners

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ABSTRACT

Connections with metal dowel-type fasteners are important details in timber construction, connecting single members and elements to larger structures. The load-carrying capacity can be described by different failure modes of the fasteners and in the surrounding timber. These failure modes show a dependency on different dimensions and material properties. The failure can be classified into brittle and ductile failure modes based on the deformation capacity. The limited deformation capacity of the brittle failure modes has an impact on the load-carrying capacity of the entire connection with multiple fasteners. The present study takes a critical appraisal of load-carrying capacity and deformation capacity of timber connections and the implementation of their design in the Eurocode 5. By aiming for the ductile failure modes with plastic deformation of the fasteners in the design of the connection, high load-carrying capacities and high reliability can be achieved. For brittle failure modes the reduced resistance and the reduced reliability should be accounted for, especially for connections with multiple fasteners.

1. Introduction

In order to be able to build larger structures, individual timber elements are connected by means of different types of connections. The structural performance of the overall structure depends to a considerable part on the connections between different timber structural members. Connections not only can govern the overall strength and resistance but also the serviceability, durability and fire resistance. The performance of these connections depends on their applications; i.e. type of load (e.g. tension, shear), connecting materials, geometry, climate exposure, etc.

Assessments of damaged timber structures shows that connections are responsible for a large portion of failure events [1]. Despite their importance, timber connection design frameworks are not based on a consistent basis compared to the design regulations of timber structural components. Explanations for this difference in progress of design provisions for members and connections can be found in the relative simplicity of characterising mechanical behaviour of members, as compared to connections.

1.1. Types of connections

The types of connections most commonly used in modern timber engineering are, amongst others: glued-connections, dowelled, bolted, nailed or stapled connections, connections with screws or glued-in rods. The connections with fasteners can be divided into two groups depending on how the forces are transferred between the connected members. The main group corresponds to the connections with dowel-type fasteners such as dowels, bolts, nails, screws and staples. The load-carrying behaviour is characterized by bending deformation of the slender fasteners. The second group includes connections with stiff fasteners such as split-rings, shear-plates and punched metal plates. The load is transferred primarily by a large bearing area at the surface of the members.

The diversity of connections types is used in practice and these types have infinite variety in arrangement. This usually precludes the option of testing large numbers of replicas for a reliable quantification and verification of statistical and mechanical models.

1.2. Design of connections in timber structures

The structural performance of single connections depends on

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different elements with individual material and individual geometrical properties. Due to this complexity, a straightforward comparison of acting stresses and corresponding strength as done with timber members is hardly possible for the design of connections. Mechanical models have been developed in order to explain the structural behaviour of connections and in order to handle the variety of possible arrangement of connections in timber structures.

One of the challenges for the implementation of mechanical models and provisions for the design of connection in codes is to account for the different characteristic properties and the different failure modes. For a reliable design the entire system of the connection (including all individual components) has to be assessed.

Connections consisting of components of different materials, such as timber and metal fasteners, may benefit from the much smaller variability of the properties of the metal elements and, hence, from the considerably lower safety factors for the metallic fasteners when evaluating the reliability [2]. In the design equations in the current European design code for timber structures EN 1995 (Eurocode 5, EC5 [3]), this benefit amounts to about 15% [4]. The reliability based design concept offers a high potential for further enhancement of the currently applied procedures in order to benefit from the full potential of timber and hybrid structures.

1.3. Some aspects on ductility for design of timber structures

Connections are important structural details and are responsible for a large portion of failure events. Inadequate connections were found by Foliente [5] to be the primary cause of damage after extreme events such as storms or earthquakes. Ductility of the connections offers the potential for redistribution of loads in the structure as a measure for robustness [6]. A detailed discussion of the importance of ductile failure modes in connections was done by Mischler [7,8]. In order to achieve the desired level of ductility, minimum dimensions, spacing and edge- and end-distances have to be satisfied. In practice, geometrical constraints may lead to dimensions of the connections lower than necessary to achieve ductile failure and desired high load-carrying capacities may require higher number of fasteners and smaller spacing and distances. This seems adequate especially if the desired load-carrying capacity can be obtained, however the resulting brittle failure modes may result in different consequences of failure. The ductility demonstrated based on a single fastener may not necessarily be achieved if multiple fasteners are applied in the connection. In addition also the change in variability of the load-carrying capacity has to be accounted for.

1.4. Content of this study

In this study the impact of ductile and brittle failure modes on the load-carrying capacity and failure behaviour of connections with multiple fasteners is discussed based on experimental and theoretical studies. It is not intended to evaluate and validate the different design models that exist for ductile and brittle failure modes of connections. This study deals with laterally loaded timber-steel-timber connections with metal dowel-type fasteners only.

2. Load-carrying capacity of connections

The load-carrying capacity of dowel-type fasteners is governed by the following characteristics:

- *Embedding strength* f_h
  The embedment strength of timber f_h is the system property that is associated to the resistance of solid timber against the lateral penetration of a stiff fastener. Properties such as dowel geometry, surface roughness or load to grain direction have an important impact on the embedment strength. The load-deformation behaviour of the dowel in lateral penetration in the timber is strongly non-linear. Nevertheless, a linear elastic - perfectly plastic load-deformation behaviour is assumed for the design. According to the test standard EN 383 [9] the embedment strength is determined as the maximum load within a penetration of the fastener in the timber of 5 mm.
- *Bending moment capacity of the dowel* M_y
  The bending moment capacity of the dowel in bending depends on the diameter and the yield strength of the dowel material. A distinct plasticity is necessary in order to achieve sufficient deformation capacity of the dowel. For simplification a linear elastic perfectly plastic material behaviour is assumed. The bending angle at which the yield moment is reached is $\leqslant 45/d^{0.7}$ degrees (d in mm) according to EN 14592 [10]. Small diameter fasteners show a higher deformation capacity whereas large diameter fastener reach the yield moment already at small bending angles. Overstrength or high carbon content of the steel may diminish the plastic deformation capacity of the dowel.
- *Axial resistance of the dowel* F_{ax}
  In the case of a failure mode where the fastener is inclined to the shear plane, the axial resistance of the dowel-type fastener can be activated. This so called rope effect causes an additional force component and can be used to mobilise the friction between the members of the connection. The axial resistance can be limited by the tensile, pulling out or head pull through resistance of the fastener. For smooth dowels the rope effect is commonly neglected due to their negligible pulling out resistance.
- *Timber failure*
  The resistance against splitting, block or plug shear failure is mainly governed by fracture mechanical phenomena and depends on the spacing, edge- and end-distances as well as the member thickness and penetration depth of the fasteners.

In addition to those four main characteristics, effects such as the effective number of fasteners or the friction between the timber members also influence the load-carrying capacity.

Connections with dowel-type fasteners usually contain more than one fastener. Modelling of the load-carrying capacity of multiple fastener connections is, however, always based on the mechanics and calculations of a single fastener. This simplification might be for practical reasons: since the mechanical behaviour of single fastener connections is rather complex, the behaviour is even more complicated for multiple fastener connections, due to the large variety of configurations which could be considered amongst other factors.

2.1. Mechanical models

2.1.1. Fastener failure: European yield model

The resistance of laterally loaded dowel-type timber connections is commonly determined as the minimum of the capacities according to the so called European Yield model (EYM) that is based on Meyer [11], who included the plastic section modulus in the models by Johansen [12]. Johansen used the elastic section modulus in his studies and analysis. These failure modes describe the embedment failure of the timber and/or the ductile failure of the dowel in dependency of the thickness t_i of the timber member i (failure modes $R_{I,i}$ to $R_{III,i}$ in Fig. 1). The relevant material properties are the embedment strength $f_{h,i}$ of the timber members and the yield moment M_y of the fastener. Geometrical parameters are the thickness t_i of the timber members and the diameter d of the fastener. The load-carrying capacities of the different failure modes applicable for a connection with a single internal steel plate (Fig. 1) according to the EYM are:

Failure mode I: Embedment failure

$$R_{I,i} = f_{h,i}\ d\ t_i \tag{1}$$

Failure mode II: Failure with one plastic hinge