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Review of design approaches and test results on brittle failure modes of connections loaded at an angle to the grain

Robert Jockwer[a,*], Philipp Dietsch[b]

[a] ETH Zurich, Institute of Structural Engineering, Stefano-Franscini-Platz 5, CH-8093 Zürich, Switzerland
[b] Technical University Munich, Chair of Timber Structures and Building Construction, Arcisstraße 21, 80333 München, Germany

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ABSTRACT

Connections in timber beams loaded perpendicular to grain are prone to brittle failure due to fracture induced by tension perpendicular to grain stresses in the surrounding timber. Different approaches can be found in literature and design codes to account for the reduction of load-carrying capacity in the design of the structure. In this study selected design approaches are discussed and their behaviour with regard to different geometrical parameters is analysed. The structural behaviour of connections loaded perpendicular to grain is evaluated on the basis of test results from literature. The impact of different geometrical parameters on the load-carrying capacity is demonstrated and the design approaches are benchmarked against a large number of individual test results. Recommendations for a more reliable design are given.

1. Introduction

1.1. General

In connections in timber global failure can occur either due to local failure of the fasteners and the adjacent timber or due to failure in the timber around the connection. Failure of the fasteners can be accounted for by designing them according to appropriate design rules, e.g. the so called European yield model (for dowel type fasteners) [1,2]. Design to prevent this failure mechanism includes prevention of embedment failure in the timber or failure of the metallic fasteners. However, in certain cases such a design of the connection is not sufficient because splitting of the timber next to the connection might occur, hence, design has to account for this failure as well.

Timber exhibits good strength and stiffness properties parallel to the grain but only very low strength and stiffness perpendicular to the grain. As a general rule situations where timber is subjected to tension perpendicular to the grain should be avoided. Structural details like connections, where tensile forces perpendicular to the grain are introduced in the timber, exhibit a high risk of fracture due to the low strength in combination with brittle failure mechanism of timber in tension perpendicular to grain. Careful design of such connections is required in order to reach the level of reliability required by design codes. Design procedures for such details can be found in literature. These exhibit different degree in complexity.

In this paper the failure mechanisms of unreinforced connections loaded perpendicular to the grain will be explained, corresponding design approaches will be evaluated and benchmarked against test results from literature. Following this, recommendations for a more reliable design of such connections will be given.

1.2. Types of connections loaded perpendicular to the grain

Connections loaded perpendicular to the grain are often made by means of nails, dowels, bolts, (self-tapping) screws, glued-in rods or shear connectors. The number of fasteners in a connection depends on the type of fastener used. Small diameter fasteners like nails or rivets are often used in larger quantities within one connection whereas large diameter fasteners like bolts, glued-in rods or shear connectors are also used individually.

Connections can either be made as timber/timber connections which is often the case for shear connectors, or can be made in combination with steel parts such as (3-dimensional) nailing plates or dowelled slotted-in metal plates. Glued-in rods or self-tapping screws can directly be loaded in tension and do not need additional elements for hanging loads.

1.3. Geometry

The geometrical properties and denotations of a connection loaded perpendicular to the grain are illustrated in Fig. 1. The level of tensile stresses perpendicular to the grain depends amongst others on the

* Corresponding author.
E-mail addresses: jockwer@ibk.baug.ethz.ch (R. Jockwer), dietsch@tum.de (P. Dietsch).

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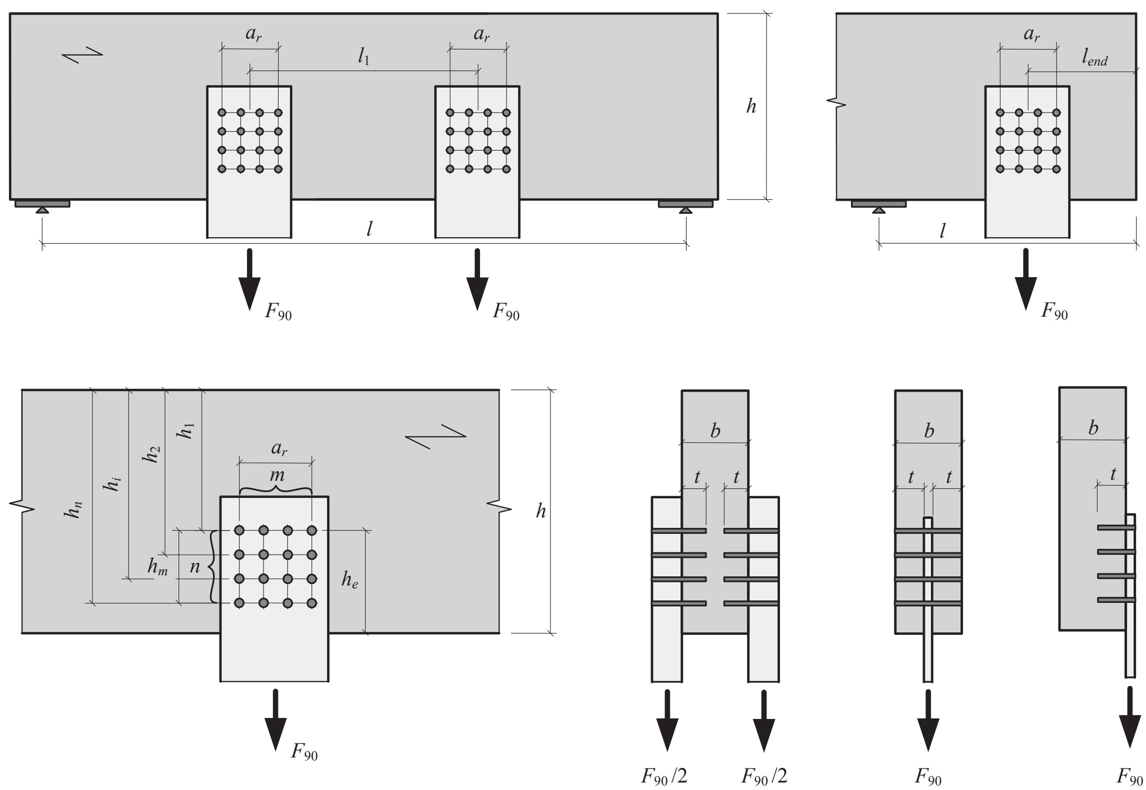

Fig. 1. Geometric parameters of connections loaded perpendicular to grain.

distance, h_e, between the loaded edge of the member and the top row of fasteners of the connection. This distance, expressed as a portion $\alpha = h_e/h$ of the full member height, h, is one of the parameters with the highest impact on the reduction of load-carrying capacity in connections loaded perpendicular to the grain. The relative load-carrying capacity decreases with increasing beam height due to size effect of the timber volume stressed in tension perpendicular to grain [3,4]. The impact of the beam width, b, on the load-carrying capacity is often assumed to be linear.

The relevant dimensions of the connection are the connection width, a_r, and the connection height, h_m. The geometry of the connection can be described by the number of columns m and rows n of fasteners. The position of specific fasteners in the connection can be specified by h_n, the distance between the n^{th}-row of fasteners to the unloaded edge. In case of multiple connections the distance between adjacent connections is l_1. The distance of the connection to the end grain can be denoted by l_{end}.

2. Review of design approaches

2.1. General

Failure of connections loaded perpendicular to the grain due to splitting has often been discussed in literature. A comprehensive review of existing design approaches was made by Schoenmakers [5]. An overview of the background and relation of the existing design approaches is illustrated in Fig. 2. Existing design approaches are based either on stress criteria such as the approach in the former DIN 1052 [6], proposed by Ehlbeck et al. [7] and the approach in the design handbook Lignum HBT 2 [8] or on fracture mechanics theory such as the design approach in EC5 (EN 1995–1-1) [1] proposed by van der Put [9]. The linear elastic fracture mechanics (LEFM) approach developed by van der Put [9] was extended and adapted e.g. based on quasi-nonlinear fracture mechanics (NLFM) by Jensen et al. [10] or semi-empirical theories by Ballerini [11], Ballerini and Rizzi [12]. Mixed mode failure in tension perpendicular to the grain and shear was accounted for in the studies on Finite-Element models by Franke and Quenneville [13]. Empirical based design approaches are presented by Quenneville and Mohammad [14] and Lehoux and Quenneville [15] based on the design of rivet connections.

The approaches show different degree of detail with regard to geometrical and material parameters. The beam height h, the relative connection height α and the beam width b are always accounted for but not all approaches account for the geometry of the connections. In addition the location of the connection along the span of the beam is only accounted for in some approaches. A summary of the parameters taken into account by the different approaches is given in Table 1.

The type and diameter of the fasteners is only accounted for by the design approaches in the former DIN 1052 based on Ehlbeck et al. [7] and in HBT 2 [8] based on Gehri [16]. The effective beam width b_{ef} is reduced in these approaches in order to account for early splitting in the vicinity of fasteners with large penetration depth t or high slenderness $\lambda = t/d$.

Zarnani and Quenneville [17] also propose to differentiate between full and partial splitting of the beam and account for the effective embedment depth of fasteners. For partial splitting the load-carrying capacity of the fasteners is relevant for the design whereas splitting failure of the surrounding timber is decisive for full splitting.

2.2. Material properties used in the approaches

Different material properties are used in the approaches due to their different underlying theory. The approaches by Möhler and Siebert [21] and Gehri [16] are based on strength theory and were fitted to experimental data. The material parameters in these approaches are related to a tensile strength perpendicular to the grain in the connection, however, a direct use of strength values determined according to e.g. EN 408 [22] is not possible.

In contrast, the approach by Ehlbeck et al. [7] uses the general value of tensile strength perpendicular to the grain, $f_{t,90}$. The definition of this