Construction and Building Materials 176 (2018) 14–23

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Fracture behavior of wood-steel dowel joints under quasi-static loading

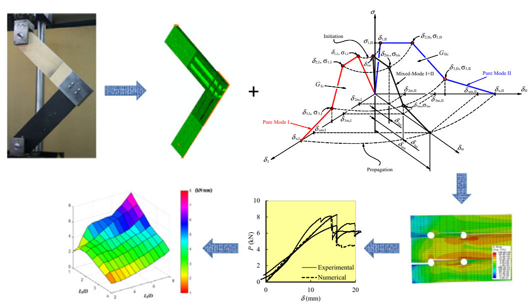
N. Dourado [a,*], F.G.A. Silva [b,c], M.F.S.F. de Moura [b]

[a] CMEMS-UMinho, Departamento de Engenharia Mecânica, Universidade do Minho, Campus de Azurém, 4804-533 Guimarães, Portugal
[b] Faculdade de Engenharia da Universidade do Porto, Departamento de Engenharia Mecânica, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] INEGI – Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal

HIGHLIGHTS

- Dowel-joints involving wood and steel were experimentally and numerically studied.
- Influence of dowels spacing on stiffness and moment-carrying capacity were analyzed.
- Numerical analysis considering a mixed-mode cohesive zone model was performed.
- Several scenarios were studied numerically to define appropriate dowel arrangements.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 March 2018
Received in revised form 28 April 2018
Accepted 30 April 2018

Keywords:
Wood
Dowel-joints
Fracture behavior
Finite element analysis
Cohesive zone modelling

ABSTRACT

This study analyses a common L-shape configuration formed by wood members and a thick metal plate, duly fastened with steel dowels. Four connecting arrangements were experimentally tested, considering different values of space between dowels and distance to the boundary edge, which allowed measuring the initial stiffness and moment-carrying capacity. A three-dimensional finite element model, including a trapezoidal bilinear cohesive law, was developed to reproduce mixed-mode loading through cohesive zone modelling. Very satisfactory agreements between numerical predictions and experimental results were registered, regarding the full-extension of the load-displacement curves and damage profiles of the joints. In light of these, the model was applied in a larger range of possible combinations of distances to get global trends of the initial stiffness and moment-carrying capacity of these joints.

1. Introduction

Steel dowel joints are among the most used solutions to assure the connection of wooden members due to manufacture and in-situ assembling easiness. This solution is frequently employed in combination with other metal parts (connection plates) providing anchor points to fasten several members. Steel dowel joints are very appealing in architecture and civil engineering, because they allow constructing lightweight buildings with superior aesthetic quality, while providing better protection against fire [1] when compared with solutions employing adhesives. These features are important requirements for those designers who are engaged in constructing wooden skyscrapers, using clear and cross-laminated timber.

Despite its great utility, steel dowel joints are viewed as stress concentration inducers, as they require holes drilled in wood members. In addition, these solutions are designed to transmit loads within very confined regions of the wood members. Moreover, the mismatch stiffness that exists between steel-dowels and wood, also contributes to create stress concentrations in the interfaces. Low strength of wood perpendicular to grain is another important handicap of this joint solution, which may cause brittle splitting and shearing out of dowel joints. These observations are at the origin of a frequent association of steel dowel joints to weak points in wooden structures. These aspects unsettle experts in building

* Corresponding author.
E-mail address: nunodourado@dem.uminho.pt (N. Dourado).

https://doi.org/10.1016/j.conbuildmat.2018.04.230
0950-0618/

construction and therefore should capture the attention of the research community to come up with accurate procedures that allow designing steel dowels joints efficiently.

The design of dowel joints for timber construction is currently performed using an analytical approach based on the Johansen's yield model [2–4]. This model considers a perfect elasto-plastic behavior for both wood and the connecting member, which cannot be viewed as a realistic procedure. It also assumes that the embedding strength of the connecting region is a material property, though it results from a combination of geometrical and material parameters. In this context, several tests to undergo the assessment of the embedding strength are required, following the EN383 standard [5]. Johansen's model is also known for its non-observance for brittle failure of wood due to cracking and the incapacity to take into account three-dimensional effects of the fastener to the wood contact. Some failure mechanisms in wood have a brittle nature, while others are characterized by a progressive development of the damage extent that softens the material. This behavior is not taken into account by the Johansen's limit analysis, because wood crushing in the area of contact with the dowels and plastic collapse of dowels are the sole aspects that are considered. As non-linear damage mechanisms in wood are spread through a so-called fracture process zone (FPZ) [6] of non-negligible size, it turns out that Johansen' analytical model is not suitable to perform the correct design of structural details like dowel joints, where damage is likely to occur. Jensen [7] has given an important contribution that combines fracture mechanics (mode I) considerations and beam on elastic foundation theory. This author analyzed the splitting failure in moment-resisting dowel joints, considering that damage in wood is due to perpendicular-to-grain loading of a single dowel. This study culminated with a series of predictions on the influence of edge distances and end-distances in dowel joints, validated by experimental data. A relevant aspect regarding this approach lies in the assumption that mode I fracture energy is a governing (and sole) material parameter. However, it should be noted that splitting failure is more accurately modelled if mixed-mode loading is considered. Though split cracking modelling of centrally loaded beams is accomplish by means of available analytical approaches in design codes [4,8–10], very few attempts have been made to cover the splitting on moment-resisting joints [7].

The analysis of the mechanical behavior of steel dowel-joints through finite element modelling (FEM) is a recent approach, that allows taking into account many material and geometrical parameters simultaneously. Most of the published studies that employed FEM have been performed using a two-dimensional approach, either in the form of the Johansen's model [11,12], or previewing load-carrying capacity both perpendicular and parallel to grain, by combining fracture mechanics concepts [13,14]. Four studies concerning the 3D-FEM modelling of steel dowel-joints in wood (*Pinus pinaster* Ait.) with experimental validation are due to Xu et al. [15], Santos et al. [16,17], and Caldeira et al. [18]. With the exception of the first work, all the referred studies simulated wood (*Pinus pinaster* Ait.) orthotropic behavior in the three anatomic directions of wood (transverse isotropy was used by Xu et al. [15]), using elastic properties obtained in other studies by co-workers. Santos et al. [16,17] simulated the joint elastic stiffness obtained experimentally, while the later allowed reproducing the load–displacement curve in its full-extension using a linear softening cohesive zone law. Moment-carrying implications were only analyzed by the study of Caldeira et al. [18]. These authors analyzed the mechanical behavior of dowel-joints by cohesive zone modelling which is a powerful tool to understand the implications of the geometrical parameters on the global strength and stiffness of a structure. This numerical procedure considers elastic and fracture properties of wood in its anatomical orientations, and includes a damage law that describes damage onset and propagation under mixed-mode loading.

The experimental praxis on joints with steel side members allows concluding that wood undergoes softening in compression parallel to grain and hardening perpendicular to grain [19]. Hence, the consideration of a model that allows differentiating the mechanical response of wood according to the predominant load orientation relative to grain is a crucial aspect. Bouchair and Vergne [20] employed a plastic flaw rule based on the Tsaï criterion to model the mechanical behavior of joints with steel side members, accounting for the evolution of plasticity of the wood member. The employment of the Tsaï criterion allowed reproducing the interaction between the principal axis of orthotropy. The model allowed assessing the effect of the clearance in the bolt connection, as well as the joint dimensions and the grain angle. The predicted stress values in the joint agreed with the ones found in the literature by other authors. Patton-Mallory et al. [21] studied the mechanical behavior of a bolted wood connection loaded parallel to grain employing a non-linear three-dimensional wood constitutive model. The analysis accounts for the elastic-perfectly plastic behavior of the employed steel pin, together with a trilinear wood compression behavior and trilinear shear stiffness degradation. The model was able to replicate adequately both the load-displacement curves and the failure modes observed in the experiments, considering the connections loaded parallel to the grain. The degradation perpendicular-to-grain was not considered in the model, which justifies the overestimation of experimental stiffness. A limitation of this model has to do with its inadequacy to replicate the experimental results in other grain orientations and higher load levels. Kharouf et al. [19] proposed a plasticity based constitutive compressive material formulation based on the Hill yield criterion to model wood as an elasto-plastic orthotropic material. The post-elastic deformation of wood induced by local crushing was simulated in bolt timber connections. Yield prediction of wood in a local scale and global deformation were accomplished by comparison with the experimental results. Moses and Prion [22] performed an analysis of the mechanical behavior of wood and wood composites, in a single-bolt connection. Wood was modeled as an elastic orthotropic material, showing an anisotropic plastic behavior with permanent deformation and energy dissipation occurring in three orthogonal planes. The authors used a yield criterion for orthotropic materials that accommodate differences in compression and tension yield stresses for each direction [23,24]. The model employed work hardening [25], together with an associate flaw rule. Load-displacement outputs, ultimate strengths and mode failure were reasonably captured for several wood species, the tested panel lay-up and connection geometry. Oudjene and Khelifa [26] proposed a constitutive model to simulate the hardening phenomenon induced by wood densification at large deformations produced by compressive loading perpendicular to grain. The authors analyzed the ductile compressive behavior of wood with densification in the referred direction relative to grain, coupling the anisotropic plasticity and the wood densification.

In this work, an experimental campaign was conducted to evaluate the mechanical performance of a moment resisting joint formed by two wood pine members and a thick metal plate duly fastened with four steel dowels in an L-shaped configuration. This solution is very common in timber construction, being frequently affected by unstable failure in the connection region. Therefore, attentive studies concerning the mechanical behavior of this type of connection may be seen as relevant in the design of timber structures. The present work analyses the effect of the space between dowels and the distance to the free edge of wood members, submitted to quasi-static loading. Hence, two dowel distances and two free edge measures were analyzed experimentally to assess the influence of the referred variables on stiffness and