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# Quasi-static behavior of moment-carrying steel–wood doweled joints

T.V.P. Caldeira [a], N. Dourado [a,*], A.M.P. de Jesus [b], M.F.S.F. de Moura [c], J.J.L. Morais [a]

[a] CITAB/UTAD, Departamento de Engenharias, Quinta de Prados, 5001-801 Vila Real, Portugal
[b] UCVE/IDMEC-LAETA, Departamento de Engenharias, Quinta de Prados, 5001-801 Vila Real, Portugal
[c] Faculdade de Engenharia da Universidade do Porto, Departamento de Engenharia Mecânica, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

## HIGHLIGHTS

- Dowel-joints involving wood and steel were experimentally and numerically studied.
- Influence of dowels spacing on load-carrying capacity and stiffness was analyzed.
- Numerical analysis considering a mixed-mode cohesive damage model was performed.
- Numerical tool is apt to define the best dowels position to avoid brittle failure.

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## ABSTRACT

Dowel-joints involving wood and steel plates were experimentally and numerically studied. The main objective was to analyze the influence of dowels spacing and dowel-to-end distance on load carrying capacity and stiffness of the structure. A particular attention was dedicated to failure type observed in the experiments, particularly the crack path in the vicinity of the dowels. A three-dimensional finite element analysis considering mixed-mode (I/II/III) cohesive zone modeling was performed. It was verified that the numerical model is able to reproduce with good accuracy the initial stiffness, ultimate load, locus of the damaged zone and the crack path observed in the experiments.

## 1. Introduction

Wood structural applications have been increasing in occidental countries stimulated by ecological and economical reasons. Actually, wood is the only building material that is wholly renewable, being recognized as energy efficient in production, processing and use [1]. Nevertheless, its use in structural applications is still considerably limited due to lack of adequate failure criteria used in design codes. Therefore, special attention might be dedicated to structural details involving wood connections, since they commonly constitute a source of failure in timber construction. In this context, dowel-joints have been investigated due to their importance regarding the enhancement of strength and ductility, as well as energy release [2]. Load-carrying capacity of dowelled-joints is strongly influenced by the connection geometry, material conditions and loading type. Resistance and durability of timber structures is affected by the performance of joints, being recognized as the weakest point in a structure. In fact, since joints act as discontinuities in a structure, they are responsible for the reduction on the global strength since they are usually a source of stress singularities.

The design of timber mechanical connections is presently based on the Johansen's yield model [3]. This analytical model however does not take into account some observed modes of degradation characteristic of wood, e.g. cracking parallel-to-grain induced by tearing actions (mode I failure) and failure parallel-to-grain due to shear stresses (mode II and III) [4]. In fact, some observed failure mechanisms in wood are clearly brittle, while others undergo progressive damage growth that gradually softens the material. However, Johansen's limit analysis only accounts for crushing of wood beneath dowels as well as for plastic collapse of dowels, which obviously is quite limitative since damage in wood frequently spreads over a considerable area leading to final brittle collapses. Indeed, since failure in wood is characterized by the development of a non-negligible fracture process zone (FPZ) [5,6], the analytical model proposed by Johansen is recognizably an inaccurate procedure to perform the correct design of dowel-joints. Other analytical formulae have been proposed in the literature for modeling the splitting of beams loaded perpendicular to grain by connections, using fracture mechanics considerations [7]. These formulations are based on important assumptions, namely they consider the mode I fracture energy as the governing material parameter.

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[*] Corresponding author.
*E-mail address:* nunodou@gmail.com (N. Dourado).

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However, in general the splitting fracture involves always mixed-mode loading. Neglecting the mixed-mode loading results in conservative predictions. Another important limitation of the analytical models is that their fundamental equations were essentially derived for a point load. The situation of multiple dowel connections has been addressed by means of empirical or semi-empirical corrections [7]. Despite analytical models have been adopted in design codes for split cracking modeling of centrally load beams by joints, very few attempts have been made to address the splitting on moment-resisting joints [8]. In reference [8], an analytical approach based on quasi-linear Fracture Mechanics is proposed for a simple moment-resisting joint, where the cracking is assumed to occur only at the dowel nearest to the end of the beam. However, in practice, cracking may occur simultaneously on several dowels, depending on dowel spacing and dowel-to-end distance.

Quasi-brittle materials like wood undergo softening damage such as micro-cracking, crack-branching or crack-bridging in the FPZ, which may represent almost the entire nonlinear zone at the crack-tip, where stresses progressively vanish along it [5]. It is recognized that failure of brittle or quasi-brittle materials frequently initiates at sharp notches. In these situations, criteria based on Strength of Materials predict stresses tending to infinity, which do not represent the physical reality. On the other hand, it can be argued that criteria based on Fracture Mechanics present several difficulties, as it is the case of the existence of a pre-crack or defect whose localization in a real structure may not be obvious *a priori*. Consequently, the employment of cohesive models [9] acquires special relevancy in the sense that they enable overcoming the disadvantages inherent to the application of Strength of Materials theories, as well as Fracture Mechanics concepts, since these approaches are both considered in cohesive models. In fact, these models employ a Strength of Materials criterion to simulate damage initiation and Fracture Mechanics concepts to deal with crack growth. Therefore, the consideration of an initial defect in the material becomes unnecessary and the problems related to stress singularities are minimized. Thus, the entire failure process can be properly simulated allowing a more adequate procedure to perform the design of dowel-joints.

In this work an experimental analysis involving moment-resisting dowel connections between side steel plates and a central wood member was performed. The goal was to assess the influence of the dowels spacing and the dowel-to-end distance on the load-carrying capacity and stiffness of the joints. This kind of moment-resisting joints is very prone to splitting cracking, which is essentially a brittle type failure mode. Therefore, the authors propose a three-dimensional numerical model based on mixed-mode (I/II/III) cohesive zone modeling [10] to estimate the stiffness and the strength of these joints. In the cohesive zone model a quadratic stress criterion was used to deal with damage onset and the linear energetic criterion to simulate damage propagation. Contact conditions were imposed between dowel connectors and the wood member.

## 2. Experiments

Steel–wood–steel moment-resisting doweled joints were prepared to undergo quasi-static three-point-bending tests (Fig. 1), formed by a wood member and two metal (steel) plates. *Pinus pinaster* Ait. was chosen to fabricate wood members. Wood moisture content was established in the interval 11–13% after being conditioned at 20 °C and 65% Relative Humidity (RH) until equilibrium has been reached. Parts were machined sufficiently distant from the stem pith to obtain specimens of mature wood and not much influenced by the curvature of annual rings. Wood members were machined in order to match the radial direction (*R*) with the load *P* direction, and the longitudinal (grain) direction (*L*) with the specimen length (Fig. 1). Wood members were produced from clear mature wood cut from a single wood log. Once machined, these members were conditioned in the laboratory to reach the necessary equilibrium conditions before testing. Two steel dowels (diameter *D*) were used to connect the wood member with a pair of steel plates. Also, a pair of fasteners (length of 30 mm) was fixed with screws at the opposite side of the beam to assure the parallelism of the steel plates in the course of the loading process. The entire assembly was simply supported on two rigid cylinders and loaded at the top of the side steel plates through a cylindrical device. As shown in Fig. 1 the loading (*P*) line was kept at the mid-distance between both dowels. Testing geometries were formed to compose nine different series according to the selected dowel space ($L_1$ in Fig. 1) and the distance to the boundary edge ($L_2$). Thus, $L_1$ and $L_2$ were assumed equal to 3*D*, 5*D* and 7*D*, with $D = 14$ mm. Wood members present a length of 400 mm and the loading-span *L* of each test series is a function of $L_1$ and $L_2$ (see Table 1).

It should be noticed that the Eurocode 5 [11] establishes the dimension of 7*D* as the minimum value to be used as the space between dowels ($L_1$) and to the boundary edge ($L_2$). The arguments sustaining this measure have to do with the fact that it allows maximizing the joint efficiency when multiple joints are used. The reason for this is that if the dowels are positioned very close to each other, then they may act as a single one, thus failing the potentials that could be issued from the use of multiple joints. However, the reduction/elimination of brittle failure modes in wood joints is not previewed in the Eurocode 5 [11]. In order to assess the influence of different distances on fracture behavior these aspects were thoroughly analyzed in the present work. Therefore, quasi-static three-point-bending tests were performed using an INSTRON 1125 testing machine (Fig. 2), with a 100 kN load cell capacity. The experiments were instrumented with two Linear Variable Displacement Transducers (LVDT) from Applied Measurements®, model AML/EU ± 10-S10: ±10 mm, which allowed measuring the average displacements of the dowel extremities with respect to the machine base. Tests were performed under crosshead displacement control, with a displacement rate set to 0.3 mm/min. This value was defined to achieve the ultimate load $P_\mathrm{u}$ in less than 3 min in order to avoid the activation of viscoelastic mechanisms in wood [6]. Both load (*P*) and displacements ($\delta$) were recorded during the experimental tests.

## 3. Numerical analysis

### 3.1. Cohesive zone model

In order to simulate damage initiation and propagation in the vicinity of the dowel joint, a cohesive mixed-mode damage model was created. The simplest linear softening relationship between stresses and relative displacements was assumed (Fig. 3). Considering a pure mode loading, the local strength $\sigma_{\mathrm{u},i}$ ($i$ = I, II, III) and the fracture energy $G_{ic}$ (area of the triangle corresponding to pure-mode model) are input properties that must be determined in advance. Hence, considering a pure mode loading, damage is initiated when $\sigma_{\mathrm{u},i}$ is attained (which corresponds to the onset relative displacement $w_{\mathrm{o},i}$) and grows as a function of a damage parameter, which is defined from the relative displacements $w_i$ [10]. Total failure at a given integration point is attained when the relative displacement reaches $w_{\mathrm{u},i}$, which is defined equating the triangle area to $G_{ic}$ [10].

Generally, structures and particularly the joints behave under mixed-mode loading, which requires a specific formulation to account for these complex-loading cases. Therefore, an extension of pure-mode model involving the contribution of three loading modes is presented. Hence, the mixed-mode (I/II/III) law is based on a quadratic stress criterion to simulate damage onset,

$$\begin{aligned} &\left(\frac{\sigma_\mathrm{I}}{\sigma_{\mathrm{u,I}}}\right)^2+\left(\frac{\sigma_\mathrm{II}}{\sigma_{\mathrm{u,II}}}\right)^2+\left(\frac{\sigma_\mathrm{III}}{\sigma_{\mathrm{u,III}}}\right)^2=1 \text{ if } \quad \sigma_\mathrm{I}\geqslant 0 \\ &\left(\frac{\sigma_\mathrm{II}}{\sigma_{\mathrm{u,II}}}\right)^2+\left(\frac{\sigma_\mathrm{III}}{\sigma_{\mathrm{u,III}}}\right)^2=1 \text{ if } \quad \sigma_\mathrm{I}\leqslant 0 \end{aligned} \tag{1}$$

assuming that normal compressive stresses do not contribute to damage [9]. Concerning damage propagation a linear fracture energetic criterion is used [10],

$$\frac{G_\mathrm{I}}{G_\mathrm{Ic}}+\frac{G_\mathrm{II}}{G_\mathrm{IIc}}+\frac{G_\mathrm{III}}{G_\mathrm{IIIc}}=1 \tag{2}$$

Taking into account the relationships between stresses and relative displacements ($\sigma_i = k_i w_i$ where $k_i$ represents the interfacial stiffness) and between energies and stresses and relative displacements $G_i = \sigma_i w_i/2$, both criteria (i.e., Eqs. (1) and (2)) can be established as a function of the squared equivalent relative displacement (i.e., $w_m^2$), which means that they are coherent. This