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A hysteresis model for timber joints with dowel-type fasteners

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ABSTRACT

Predicting the mechanical behaviour and the failure mechanism of timber joints with dowel-type fasteners requires consideration of several factors, including the geometrical and mechanical properties of the metal fastener, the physical properties of timber and the interaction between such elements. This paper proposes a numerical model where a joint is schematized as an elasto-plastic beam in a non-linear medium with a compression-only behaviour. Unlike the differential approach adopted by most of the hysteresis models published in literature, this model predicts the load-displacement response using simple mechanical relationships and basic input parameters. Furthermore, the model is capable of reproducing the effect of the cavity formed around the fastener by timber crushing, and simulates the hysteretic behaviour and the energy dissipation under cyclic conditions. Shear tests are reproduced on nailed steel-to-timber joints in Cross-Laminated Timber and results are compared to the experimental test data obtained on similar single fastener joints. Simulations lead to accurate predictions of both the mechanical behaviour (initial stiffness, maximum load-carrying capacity, global shape of the loading curve and of the hysteresis cycles) and the total energy dissipation observed in the tests.

1. Introduction

Timber structures are made of 1D (e.g. beams and studs) and 2D elements (e.g. walls and floors) fastened together with mechanical joints and connection systems that transmit the lateral shear and tension loads. Due to the high strength-to-weight ratio of timber and the connections capacity to resist the load with ductile deformations and little impairment of strength, these structures showed satisfactory performances in seismic conditions [1–5].

Mechanical joints in timber structures are assembled using dowel-type fasteners (nails, staples, screws, bolts, and dowels). Their load-displacement response depends on several factors, including the yielding moment and the withdrawal behaviour of the fastener, the embedment behaviour of timber, and the interaction between fastener shank and timber.

Eurocode 5 [6] defines the load-carrying capacity of joints with dowel-type fasteners according to the European Yield Model (EYM), originally proposed by Johansen [7]. The rope effect is included into the design equations and some limiting factors, expressed at a maximum percentage of the lateral dowel capacity of the joint, are introduced to avoid relying on the withdrawal of the fastener. Since the EYM is developed based on a plastic limit analysis, it is suitable to determine collapse loads, while it cannot be used to predict the load-displacement response under monotonic or cyclic conditions.

Alternative calculation methods were proposed since the early '50s to overcome the limitations of the EYM. Ivanov [8] developed an empirical quadratic equation to relate the strength of a nailed joint to its displacement. Mack [9] proposed a calculation model where the load-displacement response is determined as product of a series of independent factors. Finally, Kuenzi [10] reproduced a single- or double-shear joint as a beam on an elastic foundation. Using a fourth-order differential equation, this model estimated the shear and deflection at any point of the joint; however, it had limited applications since it could be used only in the elastic range of the loading curve.

In recent years, many research projects focused on developing hysteresis models able to predict both the elastic and inelastic response of joints with dowel-type fasteners. Three approaches were followed: the first one aimed at improving the results obtained with the beam on an elastic foundation, by reproducing the embedment behaviour of timber with non-linear springs [11–14]. In the second approach, the non-linear response of the joint was concentrated into hysteretic springs or simple elasto-plastic systems [15–21]. Generally, such models were used to analyse the behaviour of light-frame shear walls or full-scale timber structures, i.e. situations where computationally efficient

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algorithms are needed. Finally, the third one aimed at developing accurate schematizations of the joints where the actual material properties are assigned to the elements of the models [22–26]. Regarding this third approach, it should be noticed that significant efforts have been devoted to develop material models capable of predicting the mechanical behaviour and the failure mechanisms of timber [27–29].

This paper proposes a numerical model able to predict the load-displacement response and failure mechanisms of timber joints with dowel-type fasteners. The model is capable of reproducing the effect of the cavity formed around the fastener by timber crushing, allowing the prediction of the hysteretic behaviour and the energy dissipation under cyclic conditions. The joint is schematized as an elasto-plastic beam embedded in a non-linear medium with a compression-only behaviour. Unlike the differential approach adopted by most of the hysteresis models published in literature, this model adopts simple mechanical relationships and basic input parameters to reproduce the response of the steel and timber components of the joint. In addition to the geometrical data, the yielding moment and the withdrawal behaviour of the fastener, and the embedment behaviour of timber are the required input parameters. Such input values can be derived either from tests (carried out, e.g., according to EN 409 [30], EN 383 [31] and EN 1382 [32]) or from the experimental results and analytical formulas published in literature (e.g. [33–35]).

The model proposed in this contribution can be used to predict the response of several types of joints. In fact, with minor modifications on the boundary conditions, the response of a timber-to-timber, a steel-to-timber, and a slotted-in steel plate joint can be simulated (Fig. 1). Results obtained on single fastener joints can be employed to analyse systems where many of these elements are present. For instance, the predicted load-displacement response of a nailed joint can be concentrated into a non-linear hysteretic spring and used to investigate the mechanical behaviour of a metal connector (e.g. an angle bracket or a hold-down) or of a light-frame shear-wall.

Shear tests are reproduced on steel-to-timber joints with annular-ringed shank nails in Cross-Laminated Timber (CLT). Firstly, the mechanical behaviour of the nailed joints is validated by comparing the numerical predictions of the lateral dowel capacity with the analytical values assessed using a model proposed by Hilson [36]. The load-displacement response under monotonic conditions is subsequently investigated by reproducing typical single fastener joints shear tests in parallel and perpendicular to the face lamination of a CLT panel. Finally, the hysteretic behaviour and the energy dissipation under seismic conditions are analysed by reproducing cyclic shear tests. Numerical results are compared to recently obtained test data of nailed steel-to-timber joints in CLT, and differences are discussed. All the simulations are performed using ABAQUS software package [37].

2. Model description

The numerical model proposed herein schematizes a single fastener joint as an elasto-plastic beam in a non-linear medium with a compression-only behaviour. A key feature of this modelling technique is the presence of non-linear springs capable of reproducing the hysteretic behaviour of the steel and timber components of the joint (Fig. 1). In this study, these springs are simulated with User Element Subroutines (UELs) taken from Rinaldin et al. [20,38]. A preliminary version of this model was presented by Rinaldin [39].

2.1. Fastener schematization

The fastener is modelled as an elastic system with concentrated plasticity. The shank is discretized into a series of elastic beams interconnected with hinges (see the schematics of the numerical model in Fig. 1 and the close-up given in Fig. 2). The presence of non-linear rotational springs at the hinge locations ensures the transmission of the bending moment between adjacent beams. Furthermore Moreover, those springs control the bending behaviour once the fastener reaches its plastic deformed configuration.

The bending behaviour of the fastener is simulated as follows: at small displacement amplitudes (Fig. 3a), the deflections are due to the bending deformations of the beams, while the springs transmit the bending moment and prevent any rigid body rotation. Once the bending

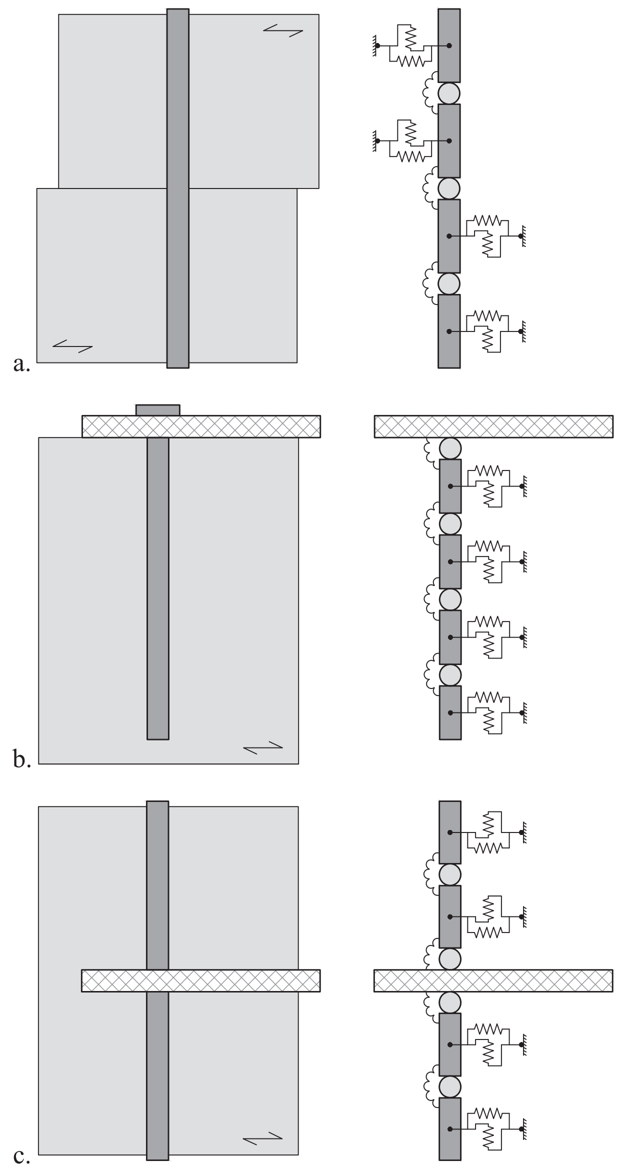

Fig. 1. Schematics of a (a) timber-to-timber, (b) steel-to-timber, and (c) slotted-in steel plate joint (left, according to Eurocode 5 [6]; right, according to the proposed numerical model).

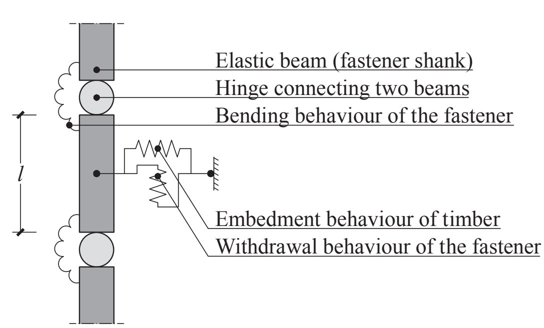

Fig. 2. Close-up of the numerical model, with description of its components.