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Finite element modelling of hysteresis, degradation and failure of dowel type timber joints

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ABSTRACT

A method for macro modelling timber-to-timber dowel type joints under shear loads using finite elements is presented. The proposed model, which includes a combination of nonlinear one-dimensional elements, is able to properly represent the hysteretic behaviour, stiffness degradation and failure of this type of joints. Experimental data from mechanical tests was used to define the macro model parameters. The proposed methodology does not require a high computational processing cost and, consequently, can be used for the nonlinear analysis of complex structural systems with a large number of connections.

1. Introduction

In recent decades the finite element method (FEM) has become a prevalent method used for analysis in structural mechanics. The study of non-linear timber models has a wide range of applications, not only in the design of new structures but also in the assessment of existing ones [1]. In particular for timber structures, using the FEM it is possible to study different types of structural systems such as timber frame [2,3], shear walls [4], log timber walls [5], light-frame walls [6,7], plywood walls [8], and floors [9]. Timber joints play a key role in structural behaviour and failure mechanism in any type of timber or mixed structures (masonry-timber [10], steel-timber [11], etc.).

Numerical model studies of different types of timber connections and materials combinations have been conducted by a number of researchers over the course of the last decades. Schneider et al. [12] summarizes some of them. Modelling studies on timber connections have ranged from simple models based on load–deformation relationship from cyclic test to highly sophisticated models, including detailed nonlinear elements for each fastener [13]. When studying dowel type joints, different approaches can be used. FEM modelling can include deformable finite sliding contact including the frictional effects between contact surfaces [14,15]. Studies suggest that simulations of dowel type timber joints should be done with three-dimensional models, because two-dimensional ones give more rigid and resistant results. Moreover, other factors should be considered such as geometric and materials nonlinearities, contact, friction, joint slip and timber fracture [16,17]. The quality of the results obtained with FEM depends on the type of element used, the discretization, the constitutive equations, the load step size, the kinematic description adopted, etc.

Complex 3D mesh models are often used to characterize a particular kind of connection or timber property and are usually performed in combination with sophisticated testing procedures such as the optical measurement of deformation fields [18]. Three-dimensional models can represent detailed yielding and failure mechanisms such as timber splitting, crushing, dowel bending and friction between components; but they have a high computational processing cost, which makes them difficult to apply in more complex modelling such as multiple nailed joints or its application in structural systems involving a large number of connections. This makes necessary the development of simplified FE models, or macro models, which represent the overall behaviour of connections. Overall response parameters such as stiffness at a given stage and load–slip curve, obtained with macro models should be approximately equal to those obtained by finite element detailed models or experimentally measured data.

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Simplified models are developed in order to produce accurate results at low computational cost and calibrated through simple mechanical testing. A common approach is to use one-dimensional elements to represent the fasteners (nails, bolts, screws), while a 2D or 3D discretization is made for timber members. Meghlat et al. [19] developed a method to simulate the behaviour of nailed and screwed timber joints using beam elements with only translational degrees of freedom and implemented it in the ABAQUS FEM software. This approach considers the linear elastic behaviour of shear timber-to-timber connections, not including the nonlinear behaviour necessary to represent the hysteretic load–slip curve. Among one dimensional models, simplified models using a combination of beam and spring elements can be found [20,21], although these models cannot be applied to hysteresis modelling without the addition of different constitutive elements, and only a bilinear fit of load–slip curves can be accomplished.

The hysteretic behaviour under reversed cyclic loading of timber connections is a subject of great relevance as the provision of ductile connections is a critical element that is often lacking in the design of a heavy timber structures to resist seismic loads [22]. Hysteretic response of walls and thus whole 3D structures can be achieved through customized hysteretic models representing the joints [23]. The hysteretic behaviour of dowel type connections under reversed cyclic loads is typically represented by load–slip or moment-rotation [24] curves as the stiffness of the connection is highly dependent on the displacement history. Particularly in the hysteretic curve of timber joints, a well-defined pinched region can be usually identified, when the dowel loses contact with the timber and moves through a reduced stiffness region and a contact zone when the dowel retakes contact and timber crushing or dowel bending occurs, resulting in the increase of stiffness.

Simplified one dimensional models incorporating a combination of constitutive elements (springs, gaps, friction sliders) are of particular interest in this study as they allow an appropriate approach to the modelling of hysteretic behaviour of timber connections. Blasetti et al. [25] have successfully used one-dimensional (1D) FE macro models to represent the dynamic hysteretic behaviour of nailed joints. This constitutive model presents the secondary cycles (reduced stiffness without increasing maximum slip), the pinched region of the load–slip curve as well as the stiffness increment of the connection when the nails are brought into contact with the timber. However, Blasetti et al. [25] model is not able to represent by itself the connection failure, but only the nonlinear elastoplastic behaviour, as it continues to provide resistance as the displacement increases.

Consequently in this paper, a new FE model is proposed, which features the ability to represent the degradation of the stiffness of the connection for large displacements including the connection failure after reaching the ultimate load, while representing adequately the hysteretic behaviour of ductile connections. Thus, a methodology developed for numerical macro modelling of dowel type joints under shear loads is presented. Laboratory testing for model calibration was performed using multiple nailed joints. A summary of implemented methodology is shown in Fig. 1.

The constitutive model presented in this work is composed of parallel branches that have a combination of simple elements (springs, friction slider and gap) to represent the load–slip behaviour of dowel type joints. Each branch consists of a one-dimensional connection element COMBIN40 available in the commercial finite element commercial code ANSYS [26].

2. Proposed FE modelling of a dowel type fastener

The structural behaviour of a dowel type fastener is represented by the load–slip curve. A typical example is shown in Fig. 2. The curve under monotonic loading exhibits an initial elastic stage with high stiffness until yielding occurs (point Fy, Dy). Then, the stiffness decreases even though the load increases as the joint slips. When the ultimate (maximum) load is achieved (point Fu, Du), the strength of the joint decreases and the stiffness is negative [27]. The hysteretic lines are usually smooth without a well-defined yield point. The loops are mildly to severely pinched. Pinching effect is caused by the loss of stiffness at small deformations. A cavity around the fastener is formed by wood crushing. The fastener shank is the only source of the connection resistance while moving through the gap [28]. From the hysteresis envelopes and monotonic curves, Yield Limit State (Fy, Dy) and Ultimate Limit State (Fu, Du) can be identified. There are various approaches to Yield and Ultimate Limit State definitions. Both can be observed as events that signify the demarcation between two behaviour states. Yield Limit State is defined as the transition of the specimen behaviour from elastic to inelastic response. The definition adopted in this research is described in Section 3.3.

The ultimate point is characterized by a near null stiffness (Ktan); and if the slip is increased a negative slope (Kdes) of the descending portion of the curve appears. From these data points, the following typical slopes may be calculated: Kfund = Fy/Dy; Kmed = (Fu − Fy)/(Du − Dy). Ktan can be obtained as the 0.1% of Kfund. The latter is the initial stiffness of the joint. The stiffness stages are represented by a schematic polygonal curve in Fig. 2.

The COMBIN40 element of ANSYS is originally composed by three parallel branches connected in series with a gap, as shown in Fig. 3. The three parallel branches are the following: (i) a friction slider, Fslide, in series with a spring, K1; (ii) a spring, K2; (iii) and a damper, C. This element has one degree of freedom at each node; in this case a nodal translation is used. The springs, slider, damper or gap properties are defined by the user; and may be removed from the element whenever is needed to modify the response of the element.

The FE macro model presented in this paper was developed using COMBIN40 elements of ANSYS. The model is capable of representing the hysteretic behaviour of the dowel-type joint while also has the ability to represent stiffness degradation and failure of the joint using the same type of elements. The proposed macro model is shown in Fig. 4, and is defined by five COMBIN40 elements of ANSYS connected in parallel, in order to obtain a two-node macro element which is able to represent the structural response of the joint. The mechanical parameters are obtained from load–slip curves of monotonic or cyclical reversed load test.

For the proposed macro model, the mechanical parameters characterizing the behaviour of the joint, can be obtained from the load–slip curve of a monotonic or a cyclical reversed load test, as well as using predictive values obtained by design specifications such as Yield Point (Fy, Dy) and Ultimate Point (Fu, Du) [29–31]. Input parameters are summarized in Table 1 for each COMBIN40 element used for a double shear nailed joint case.

The obtained response is shown in Fig. 5, in which the envelope curve and the cyclic response are approximately represented by a multi-line hysteretic model. For reverse loads a hysteretic behaviour appears, with a typical pinched and contact region. In this model, the initial load F0 is necessary for the joint to begin slip, which can be obtained as the average value of the load when the load–slip curve crosses the vertical axis in a cyclical reversed load test.

Element 1 of the proposed macro model contains a spring in series with a slider. Being the spring stiffness 100 times Kfund, this provides a minimum load value for the joint to begin slip. Element 2 contains two parallel branches in series with a gap: the first branch presents a spring in series with a slider, and the second branch a spring; Element 2 controls the hysteretic behaviour of the joint. Element 3 contains a spring in series with a slider, It presents the stiffness after yield point, Kmed, until Fu is reached.