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Joints and wood shear walls modelling I: Constitutive law, experimental tests and FE model under quasi-static loading

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ABSTRACT

This study is the first of two companions papers that present a finite element (FE) model of timber-frame structures. It introduces a versatile hysteretic constitutive law developed for various joints with steel fasteners commonly used in timber structures (nails, screws, staples, bracket-type 3D connectors, punched plates). Relative to previous models available in the literature, the proposed model improves numerical robustness and represents a step forward by taking into account the damage of joints with metal fasteners. More than 300 experimental tests are carried out on joints and used to calibrate the constitutive law for nails and bracket-type 3D connectors. An average calibration method is presented to take into account the experimental variability. 14 experimental tests are performed on different configurations of shear walls and are used to validate the proposed FE model. Both monotonic and reversed cyclic loadings are used in these quasi-static tests. The FE model predictions are in good agreement with the experimental results. The second paper will present dynamic experiments and numerical predictions of the tests, as well as the development and validation of a computationally efficient simplified modelling of timber-frame structures based on a simplified finite element model for shear walls.

1. Introduction

This paper is motivated by two facts. First, timber-frame construction is an increasingly common building system in Europe, primarily for residential single or two-story houses. These structures present many qualities, including good earthquake resistance due to the excellent strength-to-density ratio of timber and to the ductility of joints with metal fasteners, providing limited inertia forces and good energy dissipation, respectively. Second, the most recent European code for the design of earthquake-resistant buildings (Eurocode 8 [15]) has been accompanied by a new seismic hazard map in some countries. Generally, based on these revised maps, earthquake resistance calculations are now mandatory in a lot more cases and the design ground accelerations are greater than previously. Therefore, the seismic behaviour of timber-frame structures must be studied, to better understand their global and local behaviours. This study focuses on shear walls, as they contribute the most to the energy dissipation of structures.

The work presented in these papers is based on a coupled experimental/FE modelling approach. One should note that the behaviour of shear walls can also be estimated through an analytical approach [26,21], but such a method would not allow the analysis of both the global and local behaviour of a timber-framed structure. Therefore, in this study, quasi-static experimental tests on metal fasteners (nails, bracket-type 3D connectors and punched plates) are performed to calibrate their hysteretic constitutive behaviour. Quasi-static and dynamic tests on shear walls are carried out to validate the numerical model for shear walls. Because nonlinear dissipative phenomena in timber-frame structures are mainly concentrated in joints, simplified force–displacement models for joints can be derived from refined analytical or FE models [7,10,1,32,35] or by fitting the results of tests performed on joints [30]. The proposed approach is based on a multi-scale concept, as proposed previously by various authors [38,18,42,36]. Such an approach requires a behaviour law to represent the force–displacement evolution on each scale. Numerous constitutive laws have been developed over the years, from the nonlinear laws for monotonic loads [20,22,27] to hysteretic models of various complexities

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[8,39,28,40,6,11,17,43,33]. Henceforth, only the hysteretic laws capturing a damage process are discussed. Richard et al. [38] proposed a strength reduction based on a cumulative factor calculated in one direction in respect to the previously achieved strength in the opposite direction. Collins et al. [9] defined a quite similar damage process. Although most of these constitutive laws use exponential functions for the pre-peak backbone curve and hysteresis loops, the model of Ayoub [3] is defined with trilinear functions, in this model the damage process is described in detail and can be divided into four degradation phenomena: strength reduction, unloading stiffness decrease, accelerated stiffness decrease and cap degradation. The evolutionary parameter hysteretic model (EPHM) proposed by Pang et al. [37] is only defined by exponential functions (pre and post-peak backbone, unloading and loading hysteretic loops) and damage is not cumulative. The latest version of the Bouc-Wen-Baber-Noory (BWBN) model has been presented by Xu and Dolan [42]. The BWBN model is analytical and phenomenological. Its history-dependent stiffness and strength degradation provide accurate fitting of reversed-cyclic experimental tests on nailed connections and shear walls, but the BWBN does not rely on physical parameters such as displacements, forces and stiffnesses. A new model, developed by Humbert [23], can be considered an improvement of the Richard et al. [38] and Yasumura et al. [43] models and fulfils the following needs:

- Richard's behaviour law shows that for some sets of parameters (*e.g.* for a metal punched plate), an exponential function does not provide a strict analytical continuity at one end of the branch leading to numerical issues [23]. This issue is shared by all models using the exponential functions originally introduced by Foschi [20].
- The law should model asymmetric behaviour, such as that of punched metal plates for roof trusses and bracket-type 3D connectors. To the best of our knowledge, all of the aforementioned behaviour laws would require new developments to meet this need.
- For the reliability analysis of structures, it is convenient to develop a robust model defined by physical parameters such as displacements, forces, and stiffnesses, whose variabilities can be identified. Although most of the models already meet this condition, the BWBN model does not.

It is important to notice that the hysteretic behaviour of nailed wood joints governs the response of many wood systems when subjected to lateral loadings; the force–displacement backbone and hysteresis curves of shear walls and joints are then similar in shape. Thus, a common feature to all the abovementioned force–displacement models is that they can be used to describe the constitutive behaviour of joints as well as the global shear wall response to lateral forces.

In this study, a new hysteretic constitutive behaviour law for joints and timber-frame structures is proposed, and its application to the modelling of oriented strand board (OSB) and particleboard sheathed shear walls is presented. More than 260 tests on nailed joints and 50 tests on connections made with bracket-type 3D connectors are performed. The calibration of the law at the joint scale is detailed, and particular emphasis is given on how to take into account the variability of the experimental results. Tests performed on 7 different configurations (combining different specimens and vertical loadings) of shear walls are described. The development of the numerical model of shear walls is then explained. To assess its capability to predict the behaviour of different configurations of shear walls, its predictions are compared to the experimental results of the 14 tests under quasi-static loading. Experimental tests present a certain variability and the large sample size allows its quantification. Then, when comparing the deterministic predictions of the model to the experimental results, the experimental variability can be considered. Moreover, tests on different configurations are designed to estimate the model versatility.

2. Force–displacement hysteretic constitutive law

The one-dimensional constitutive law is shown in Fig. 1.

The following notations are used to describe the asymmetric feature of the modelled systems and the notion of force sign. The $\square^+$ direction corresponds to the first direction of loading in the case of reverse loading ($\square^-$ refers to the opposite direction). In the absence of a superscript, the parameters refer to both sides

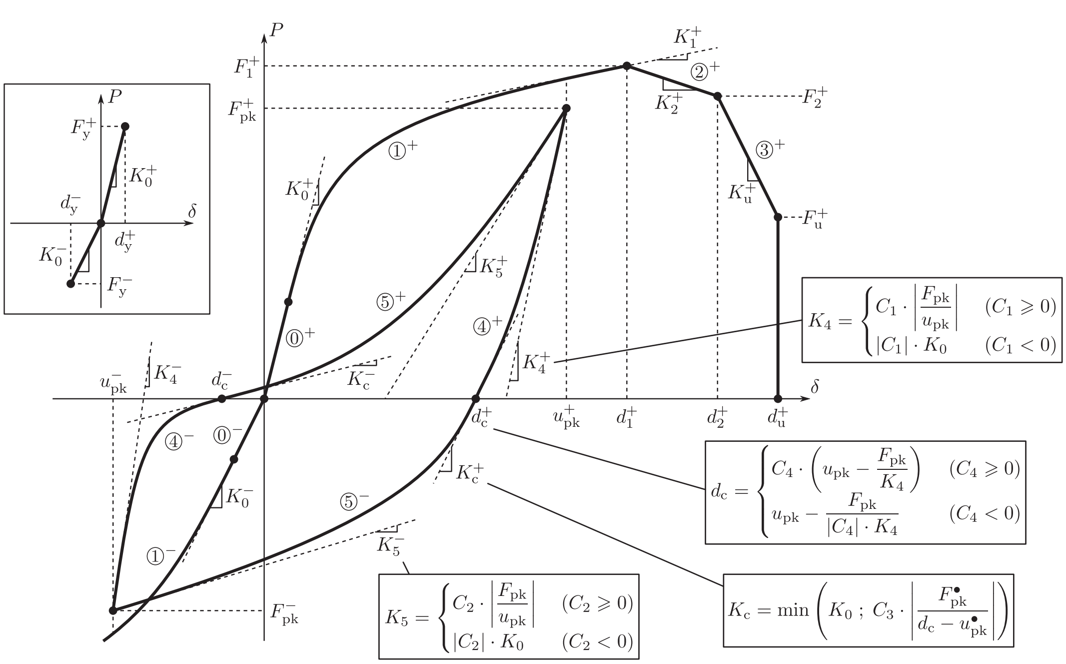

Fig. 1. Proposed force–displacement constitutive law [23].