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Numerical analysis of timber-framed wall elements coated with single fibre-plaster boards

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ABSTRACT

The paper presents a numerical analysis of the horizontal load-bearing resistance of timber framed wall elements coated with single fibre plaster boards (FPBs) that can be used in the construction of single- or multi-storey prefabricated buildings. The research deals with both the full elements (without any opening) and with elements containing an opening. The study represents a continuation of the experimental research realised in the past period.

The horizontal load-bearing capacity of FPB-sheathed timber-frame wall elements is mainly dependent on the relatively low tensile resistance and the consequent occurence of cracks in FPB. In the numerical model, the brittle behaviour of the FPB under tensile stresses is proposed to be modelled by using shell elements that allow for nonlinear material behaviour. The results of the numerical analyses proved good coincidence with the results of the experimental tests. Further, the possible impact of the wall elements with openings on the load-bearing capacity of wall systems subjected to horizontal (wind and especially earthquake) loads is discussed. A comparative study has shown that the influence may be considerable. By overtaking a part of the load these elements improve the structure's elastic resistance, while in the post-elastic phase they provide additional ductility. Also, the over-strength and the ultimate capacity of the wall system are improved. In terms of structural safety, therefore, the elements with openings have a beneficial effect during moderate earthquakes, but also in the case of a severe earthquake. It was concluded that the methods currently available in the European design codes underestimate the capacity of wall elements with openings. This may result in inadequate modelling of structural behaviour and indicates the need for more accurate methods.

1. Introduction

Timber structures represent a significant part of the construction industry in many countries around the world. One of the commonly used solutions for both single- and multi-storey buildings are the prefabricated timber structures with timber-framed wall elements as the main vertical load-bearing members. The wall elements are composed from a timber frame and the sheathing boards which are usually made of either a wood-based or the fibre plaster material. The fibre plaster boards are often preferred due their good thermal and sound insulation properties as well as their high fire resistance. In terms of the load-bearing capacity, the timber frame in general resists most of the vertical loads, while the sheathing boards provide the horizontal stability, i.e. their main function is in resisting horizontal (wind and seismic) loads. Using adequate shear connection between the components, the wall elements may be considered as composite systems taking advantage of the favourable properties of both materials.

In conventional buildings (i.e. residential, office, etc.) a significant part of the wall elements may have one or more openings for functional reasons, doors or windows. The openings reduce the stiffness of the structure, while additional problems are caused due stress concentrations at the corners. Several research papers have been published in the past discussing the influence of the openings on the load-bearing capacity of different structures, e.g. reinforced concrete shear walls [1], timber composite beams [2] and also plywood-sheathed timber-frame wall elements [3,4].

This paper presents a numerical analysis of timber-framed wall elements coated with single fibre-plaster (FPB) boards. Both elements without openings (referred to hereafter as "full wall elements") and elements with openings were analysed. The horizontal load-bearing capacity of wall elements with FPB sheathing boards is mainly dependent on the relatively low tensile resistance and the consequent occurence of cracks in the fibre plaster boards, which thus represent the weak component of the composite system. This effect is proposed to be modelled using the nonlinear shell elements and a nonlinear material model with the defined brittle behaviour under tensile stresses.

The present study is a continuation of the research work on the horizontal load-bearing capacity of wall elements realised in

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the last years. An extensive experimental study of full wall elements with different types of sheathing boards and by applying different types of reinforcement was carried out and the results were published in Refs. [5–8]. On the basis of the experimental tests, an analytical procedure was also proposed in [9,10] which proved to yield good results regarding the estimation of the behaviour of the full wall elements subjected to horizontal loads.

The horizontal load-bearing capacity and the stiffness of the wall elements with openings are in general considered to be much lower when compared to the full elements. According to the European design code for timber structures, Eurocode 5 (EC5) [11] two alternative methods for the discussed walls are proposed. By the first one (Method A), the wall elements with openings are to be disregarded and the horizontal loads should be distributed to the full elements only. By the second method (Method B), the horizontal load-bearing capacity of elements with openings is partly accounted for in a way, that the lengths of an element on both sides of the opening are considered as separate (full) elements. It should be noted, that according to EC5, the Method B is applicable for wall elements with sheathing boards made of wood-based materials only. Consequently, for the cases of the FPB-sheathed timber-framed wall panels, only Method A can be applied according to EC5.

The past experimental analyses on wall elements coated with single FPB boards and with different areas of openings, presented in [12,13], have shown that the horizontal load-bearing capacity and the stiffness of elements with openings is in reality higher and that both methods from EC5 considerably underestimate the contribution of such elements to the overall horizontal capacity of wall systems. Similar conclusions were established by Yasumura and Sugiyama [4] for the cases of plywood-sheathed timber-frame wall elements. Considering the fact that in conventional buildings a large part of wall elements (50% or even more) have openings, such elements may transmit a considerable part of the horizontal load and thus they have a beneficial impact on the overall horizontal stability of wall systems. On the other hand, in cases of multi-storey buildings with higher values of the fundamental periods of vibrations, the underestimation of the stiffness (by disregarding the wall elements with openings) results also in an underestimation of the design seismic load. From either point of view, it seems reasonable that the contribution of wall elements with openings should be accounted for, of course by considering the realistic properties of their behaviour.

The above mentioned analytical procedure [10] has been developed on the assumption that the full wall elements behave as cantilever beams having a uniform composite cross-section. When an opening is present in the wall element, however, a frame-type behaviour is expected and the analytical model considering the cantilever beam is not applicable. Therefore, a numerical study using FEM analysis was performed for the wall elements with openings and is presented here. The main objectives of the numerical analysis were, in the first phase, to establish an appropriate structural model which would prove to give satisfactory solutions in comparison to the experimental results, and in the subsequent phase, to perform a parametric study for wall elements with different areas of openings.

The studied structures have been modelled and analysed using the commercial FEM computer software SAP2000 Nonlinear v 14.0.0 [14]. The general characteristics of the mathematical modelling process are presented in Section 2, while the results of the numerical analyses are shown and discussed in Section 3 of the paper.

2. Mathematical modelling

The studied wall elements have been modelled and analysed by using the commercial FEM computer program SAP2000 Nonlinear v 14.0.0 [14].

The behaviour of the analysed wall elements is largely tied to the properties of the plaster material, i.e. its low tensile resistance, and the consequent occurence of cracks. The plaster material was therefore modelled as acting linearly elastic in compression, while in tension a stress drop occurs when the characteristic tensional resistance (f_{bt}) is reached, corresponding to the model of brittle cracking, see Fig. 1. The sheathing boards were modelled using the nonlinear shell elements offered by the SAP2000 software. According to the definition of the applied shell elements, the nonlinear behaviour was accounted for by two decoupled 1D models, one for the horizontal direction, and one for the vertical direction.

The timber material was considered as an isotropic elastic material (with the modulus of elasticity $E_{0,\mathrm{mean}}$) and the elements of the timber frame were modelled as the simple plane-stress elements. It should be noted that, due their geometry, the timber members behave predominantly as beam elements with normal stresses acting parallel to the grain, while the normal stresses in the perpendicular direction are negligible.

The mechanical fasteners between the timber frame and the sheathing boards, i.e. the staples, also require a somehow in-depth discussion. According to Eurocode 5 [11], the shear stiffness (i.e. the slip modulus K) of the fasteners at a specific point is dependent on the current value of the shear force (V_z). The corresponding three-linear diagram for the slip modulus K was introduced in [6] and is presented in Fig. 2.

In the presented numerical model a simplified shear force-slip modulus was considered with a constant value of the slip modulus through each phase (indicated by the dashed line in Fig. 2). The staples were modelled using the nonlinear link elements (springs) with a multi-linear elasto-plastic force–displacement relation, presented in Fig. 3. In order to take account of the general in-plane link between the connected elements, two perpendicular uncoupled 1D springs were used for each fastener.

The static model with the general geometry of the element and its cross-section are shown in Fig. 4.

It should be noted that the supporting conditions (as shown in Fig. 4) are considered according to the setup for the experimental tests and are defined according to Eurocod 5. The tensile (left bottom) support was arranged using three M16 bolts and two steel plates (one on each side of the wall element). The steel plates were connected to a rigid steel frame. In the numerical model, the bolts were considered as linear elastic spring supports with the stiffness equal to the slip modulus (K_{ser}) for bolts. It should be noted that the steel plates were not included in the numerical model. The compressive (right bottom) support was modelled using rigid point supports as shown in Fig. 4.

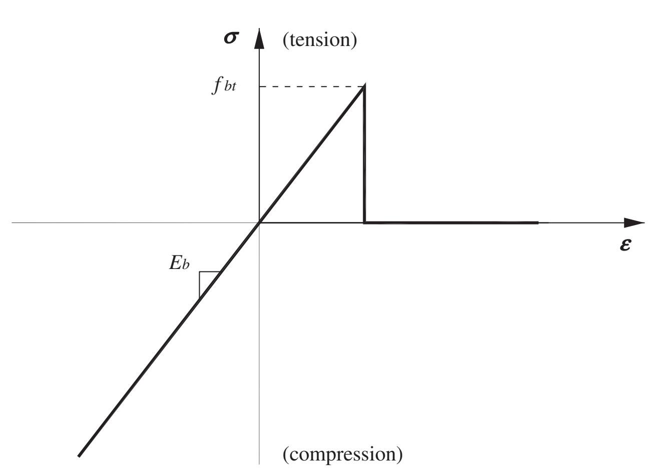

Fig. 1. Stress–strain diagram for plaster material.