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Analytical Modelling of Traditional Composite Timber-Masonry Walls

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Abstract Composite timber-masonry walls have been used in many old traditional and preservable buildings that constitute a significant part of the world cultural heritage. In this structural system the walls are composed by a timber substructure that is filled by masonry with (or without) mortar. The response of these walls to any static or dynamic loading, even of small intensity, is generally non-linear, mainly due to the complex interaction between the timber and masonry components. It is obvious that the analysis, design, strengthening and retrofitting of these composite structures demand a quite complex, reliable and effective structural model that can take into consideration all the above mentioned construction details and sources of non-linear behaviour. In the present study such a precise analytical micromodel for this structural system is further developed and demonstrated with application examples.

Keywords: Timber-masonry wall, composite traditional wall, infilled timber structure, infilled truss-work, analytical modelling

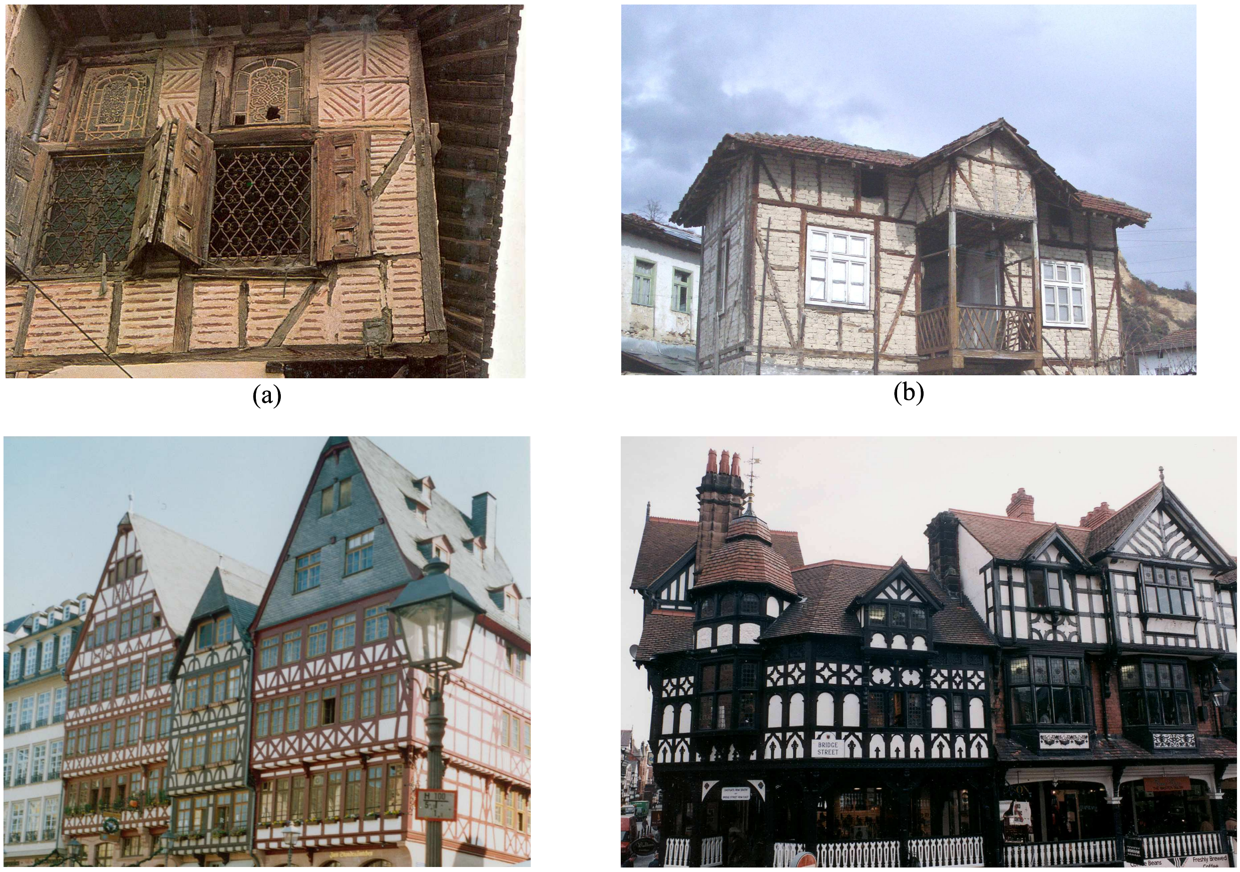
Introduction

Composite timber-masonry walls have been used for the structural system of a variety of buildings all over the world during the last centuries. Although this construction technique is rarely applied to modern structures, it has been extensively used in many old traditional and preservable buildings that constitute a significant part of the world cultural heritage. Such buildings are met in Balkan and Mediterranean countries, in North and Central Europe, in Turkey, India, Central and South America etc. (Fig. 1).

In spite of the considerably different alternative shapes of the walls shown in Fig. 1, they share several common structural features. They are composed by a timber substructure in the form of a usual flexural frame, or braced frame or even truss-work, that is filled by masonry with (or without) mortar, or just mortar alone. The connections of the wooden elements are often implemented with solitary nails or rows of nails, which allow some relaxation and relative slipping at the connection joints. Depending on the geometrical shape of the timber substructure, the structural behaviour of these walls is characterized by the derivation of axial forces and in-plane bending moments at the timber members, while the contribution of the infilling masonry to the system's stiffness, strength, and stress-state is remarkable. Therefore the timber substructure as well as the masonry infill, constitute equally prominent components of this structural system, a detailed description of which can be found in (Gulkan and Langenbach 2004).

The response of the composite timber-masonry walls to any static or dynamic loading is generally non-linear, mainly due to the following reasons: a) existence of frictional contact interface conditions between timber substructure and infill material, resulting in variable contact area during varying loading, b) potential slipping and relaxation at the connection joints of the wooden parts, c) inelastic material behaviour.

The analysis complexity of this structural system, when the need for strengthening and retrofitting a preservable structure arises, often leads practically to the replacement of the timber-masonry walls with modern conventional ones, thus altering the traditional style of the preservable structure.



(a) (b) (c) (d)

Figure 1: Old traditional buildings with composite timber-masonry walls in: a) Greece, b) Bulgaria, c) Germany, d) England

Therefore it is obvious that the analysis, design, strengthening and retrofitting of these composite structures demand a quite complex, reliable and effective structural model that can take into consideration all the above mentioned construction details and sources of non-linear behaviour. In the present study such a precise analytical micromodel (Doudoumis et al 2005) for this structural system is further developed.

Method of Analysis

Basic Features of the System's Behaviour In the timber-masonry walls the connection at the interface of timber substructure and masonry infill is usually attained by simple contact or by the presence of some mortar with low and unreliable tensile strength and adhesion capacity, which obviously could be ignored in the analytical modelling of the system. Consequently, only compressive normal and limited frictional contact stresses can be considered at this interface, while separation or slipping may occur along any parts of it. The actual contact area changes, during varying loading of winds and earthquakes, but this contact area is not a priori known. The consideration of frictional contact boundary conditions is a well working modelling approach for this problem.

At the connection joints of the wooden parts potential slipping and relaxation usually takes place, due to constructive imperfections at these joints. Code provisions for timber structures (Eurocode 5, etc.) suggest consideration of this slipping possibility by using linear springs with properly selected "slip modulus" K_s. In case that the shape of the joint prohibits slipping of certain members under compression, a special gap element can be used which prohibits penetration but allows separation with "slip modulus" K_s. Regarding the material laws of the composite timber-masonry walls, it is noted that the behaviour of each material is inelastic in general, especially of the masonry infill and of the wood and nails at the areas of the connection joints.

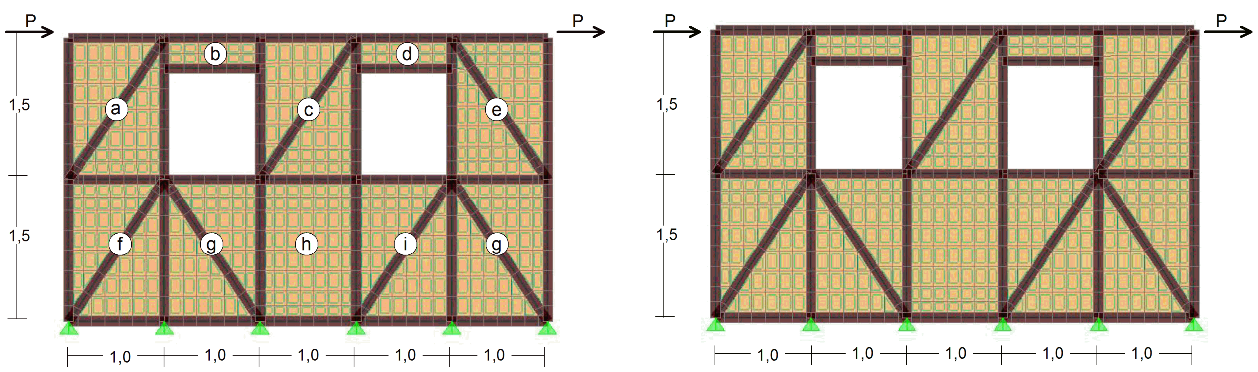
Modelling Proposals All the above mentioned are taken into consideration in the modelling approach presented below. A fine mesh of finite elements is applied to the structural system and a typical mesh of such a kind is shown in Fig. 2, which concerns the entire face wall of an one-storey small building. In particular, the wooden parts are modelled using inelastic frame elements with bilinear elastoplastic material law and predefined locations of possible plastic hinges (SAP2000, 2008), while for the infilling masonry inelastic plane-stress or shell elements are used with pressure-depended material strength (Drucker-Prager, etc.) or low-strength concrete law (ADINA 2008). The discontinuities at the ends of the wooden parts are modelled with proper release-end conditions at the respective frame elements. For the proper consideration of the finite size of frame elements' sections, rigid offsets between the neutral axis of the frame elements and the contact interface are introduced. Regarding the slipping possibility of the joint connections of the wooden parts, either linear springs with "slip modulus" K_s are introduced, or special gap elements which prohibit penetration but allow separation with "slip modulus" K_s. The finite strength of the joint connections' components of the wooden parts (wood and nails) are modelled with elastoplastic link elements that have been set in parallel with the elements that model the slipping possibility. Finally, the boundary conditions between the infilling masonry and the wooden parts are modelled using proper contact-friction bonds with Coulomb's law of dry friction (Doudoumis and Mitsopoulou 1998). At this point, the significance of the flexural stiffness of the frame elements must be underlined, which means that the flexural stiffness should not be neglected, so that the contact interaction between the infilling masonry and the timber substructure will always be activated.

Sample Application

As previously mentioned, the slipping at the connection joints of the wooden parts as well as the frictional contact conditions between timber substructure and infilling masonry, constitute primal reasons of non-linear behaviour of the system. The effects of these factors are briefly investigated in the sample application that follows.

The wall under consideration represents the entire face of a small one-storey building. The proposed micromodel (using 337 frame and 422 shell elements) is shown in Fig. 2a (model1), while an alternative model regarding the shape of the diagonal bracing of the timber structure (model2) has also been examined (Fig. 2b). These models are subjected to quasi-static cycling horizontal loading 2P=100 kN (Table1), acting at the top beam (Fig. 2). The friction coefficient takes a constant value μ=0,50 all over the interface, while the material and section properties' data are shown in Table 1.

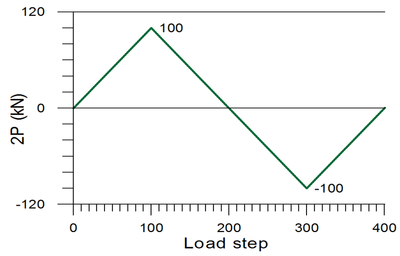
All the columns have a 3,0 m continuous length, while the top and bottom beams have a 5,0 m continuous length. Release-end conditions (for zero bending moments) are considered at the ends of the 7 diagonals and the remaining 7 beams that stand between the top and bottom of the storey's height. The finite size of frame elements' sections has been considered too.



(a) model1 (b) model2

Figure 2: Finite element micromodels of the examined composite timber-masonry wall

Table 1: Loading, material and section data

Quasi-static Loading	*Materials and Sections*	*Interface and Joints*
	Wood: $E = 12\times10^6$ kN/m^2 $G = 5\times10^6$ kN/m^2 Column sections: 10×10 cm Beam sections: 10×10 cm Diagonal sections: 10×10 cm Masonry: $E = 3\times10^6$ kN/m^2 $G = 1{,}2\times10^6$ kN/m^2 Thickness: t=10 cm	Interface friction coeff: μ=0,50 Joint slip modulus: $K_{s1} = 2\times10^3$ kN/m $K_{s2} = 2\times10^4$ kN/m

Regarding the slipping possibility at the connection joints of the wooden parts (Ignatakis and Eftichidis 2008), 3 alternative cases of "slip modulus" at both ends of all the diagonals have been examined: a) K_{s1}=2×10^3 kN/m, corresponding to typical connections with 1 nail without pre-drilling (Eurocode 5), b) K_{s2} =2×10^4 kN/m, corresponding to typical connections with 4 nails with pre-drilling and c) No slipping possibility. The slipping possibility is activated only when tension axial forces are developed at the diagonal bracing. Moreover, the assumption of linear elastic behaviour is made for all the materials and joint connections' components (wood and nails).

The existence and direction of timber diagonal bracing in each panel (A÷J) of the examined wall, gives the possibility of evaluating the influence of diagonal bracing and its possible slipping on the system's response. In Fig.3 the variation of horizontal displacement at the right top corner of the wall (which also measures the horizontal system's flexibility) during the cyclic loading is shown. We can see that:

- In model1 (symmetrical bracing): For the case of node connections without slipping possibility, the curve corresponding to positive loading–unloading (steps 1÷200) resulted to be identical (as was expected) to the curve corresponding to negative loading-unloading (steps 201÷400). For node connections with slipping possibility (cases K_{s1}, K_{s2}), the horizontal displacement in every step of positive loading-unloading (steps 1÷200) resulted to be different (greater) than that of the respective step of negative loading-unloading (steps 201÷400). This is due to slipping occurrence at the ends of the tensile diagonals, which violates the structural symmetry of the system.
- In model2 (unsymmetrical bracing): For node connections without slipping possibility, the system's flexibility in every step of positive loading-unloading (steps 1÷200) is less than the flexibility during the respective step of negative loading-unloading (steps 201÷400). However for node connections with slipping possibility (cases K_{s1}, K_{s2}), the flexibility in every step of positive loading-unloading (steps 1÷200) is greater than that of the respective step of negative loading-unloading (steps 201÷400). It should be clarified that the results obtained here are due to the specific values considered for the slipping modulus K_s, the axial stiffness of the timber diagonals and the axial stiffness of the compressive diagonal zones of the infilling masonry.

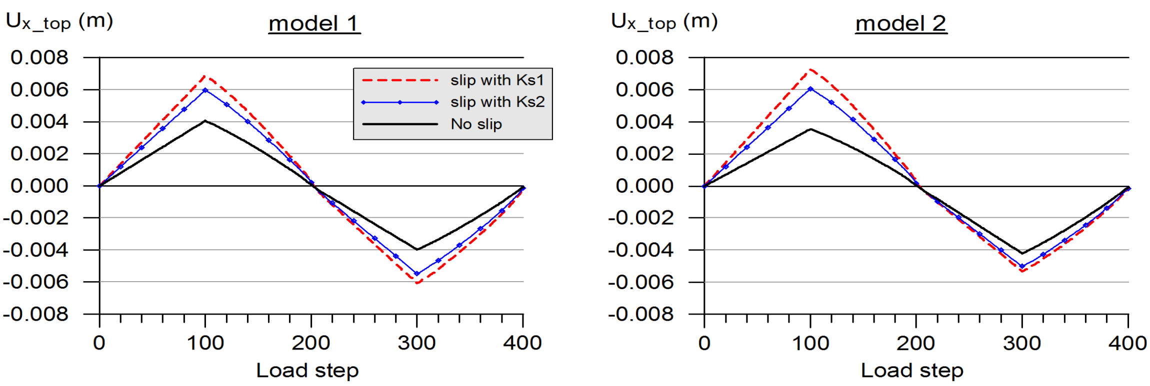


Figure 3: Horizontal displacement at the right top corner of the examined wall

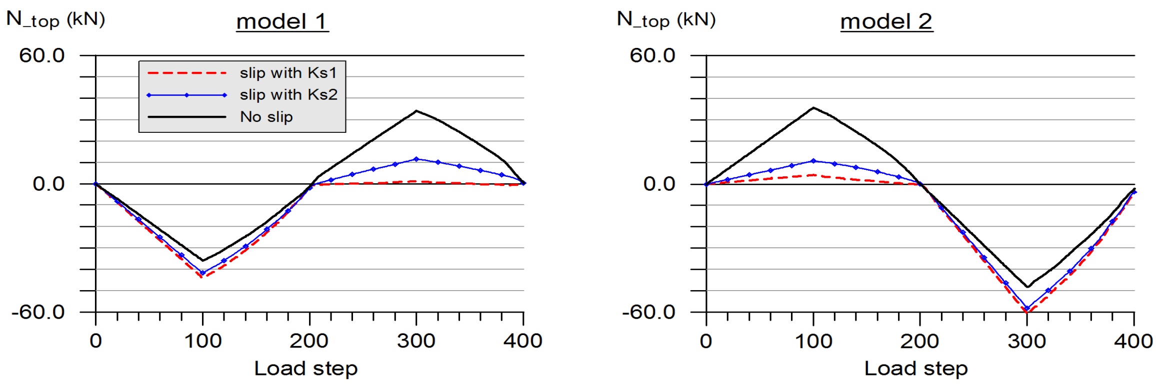


Figure 4: Axial force variation of the timber bracing element in panel E

It should also be clarified that the axial stiffness of the compressive diagonal zones of the infilling masonry (see Figs 5,6) is not a priori known, but is indirectly obtained as a result of the solution of the respective finite element problem, thus definitely depending on the timber-masonry contact interface conditions and on the geometry of the timber and masonry substructures. Moreover, the response of the system and its individual structural components definitely depend on the time-history of the applied loading (load path). This conclusion is obtained from Fig. 4 which shows that, in all the examined models, the axial force curve during positive loading (steps 1÷100) is quite different than the curve of the respective unloading (steps 101÷200), and the same happens during negative loading-unloading. Fig. 4 also shows that the "slipping modulus" K_s considerably affects the axial forces of the tensile diagonals, but has a lesser effect on the axial forces of the compressive ones.

The deformed shape of certain examined models are shown in Figs 5 and 6, together with the distribution of effective stresses (Von Mises) within the infilling masonry, for the extreme values (2P=±100) of the cycling loading. We can discern the actual contact areas between timber members and infilling masonry as well as the joint slipping at the ends of the tensile timber diagonals. We can also discern the diagonal zones with stress concentration along the shortened diagonals of the respective infilling panels, especially when along these diagonals timber elements do not exist. Moreover it is evident that the stress concentration is highly localized at the very near areas of the compressive corners of the infilling masonry, which also constitute the most vulnerable areas of the masonry under horizontal loading.

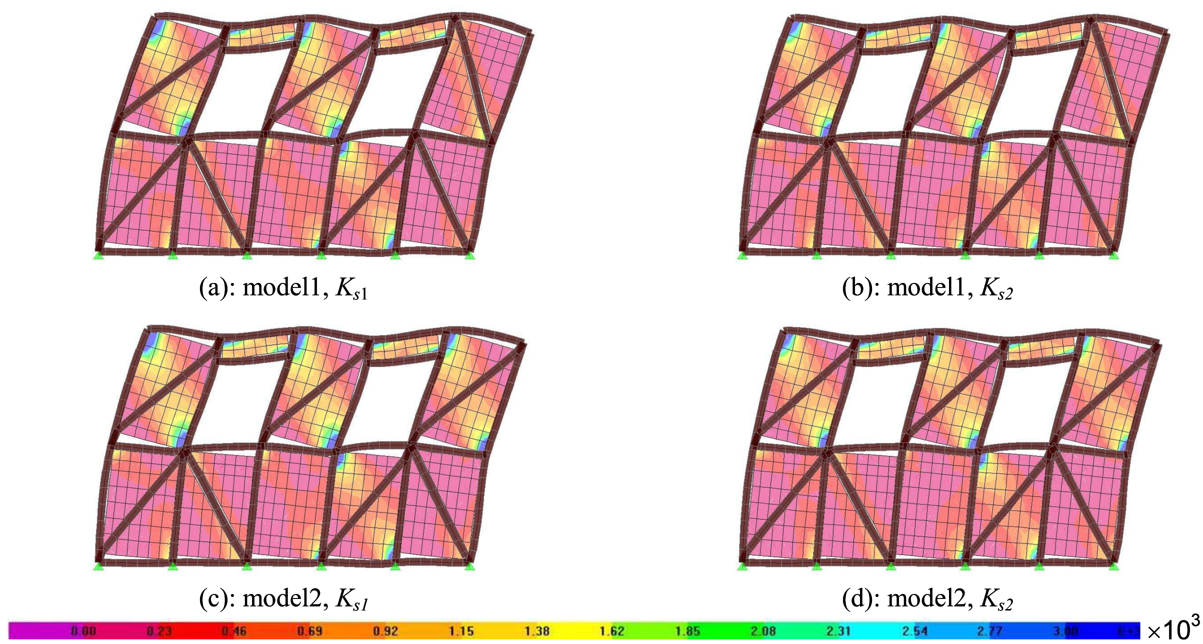
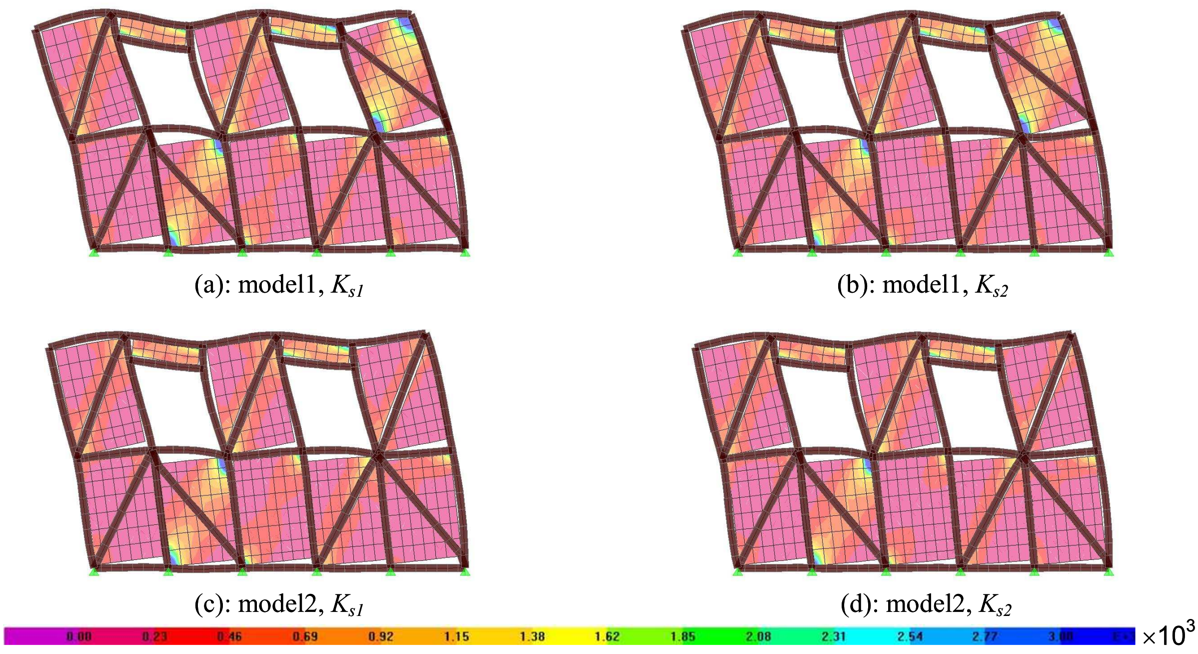


Figure 5: Deformed shape and distribution of effective stresses within masonry at load step 100



(a): model1, K_{s1} (b): model1, K_{s2}

(c): model2, K_{s1} (d): model2, K_{s2}

Figure 6: Deformed shape and distribution of effective stresses within masonry at load step 300

Conclusions

The proposed and further developed micromodel can represent with sufficient accuracy the complex non-linear structural behaviour of the composite timber-masonry walls. The examined numerical applications showed that the contact boundary conditions at the timber-masonry interface, the arrangement and orientation of the timber diagonal bracing and the construction details at the joint connections, can considerable affect the response of the overall system and its individual components under quasi-static or dynamic loading. They also showed that the timber substructure as well as the masonry infill, constitute equally prominent components of this structural system. It is evident that the uncertainties of the material laws and the construction details in general of these composite walls, affect much more the results of the system's response than the inevitable imperfections of the suggested micromodel.

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