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ANALYTICAL MODELING OF MASONRY-INFILLED TIMBER TRUSS-WORKS

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Abstract. *Masonry infilled timber truss-works is a kind of wall that has been used for the load bearing system of many residential buildings all over the world during the last centuries. In this structural system the walls are composed by a wooden skeleton, with vertical, diagonal and horizontal beam-like elements, that is filled with brick-masonry or stone-masonry with (or without) mortar, or just mortar alone. The static behavior of the wooden skeleton is characterized by the development of axial forces and bending moments, while the contribution of the infilling material in the system's stiffness, strength, and stress distribution is remarkable.*

In the present paper a detailed analytical finite-element model of this structural system is formed and studied. The wooden elements are modeled with beam-column elements, the infilling material with plane-stress elements, while the boundary conditions between the infilling material and the wooden elements are modeled with proper contact bonds. Elastic or inelastic constitutive laws can be used for the materials and the joint connections of the wooden elements. Numerical applications of the proposed model, with comparisons to other models, are presented for several cases of simple walls without openings, as well as for the case of a complex wall with openings, representing the entire face of a building storey.

1 INTRODUCTION

Masonry infilled timber truss-works is a kind of wall that has been used for the load bearing (structural) system of many residential buildings all over the world during the last centuries. It has been used in Portugal and Italy as an earthquake-resistant structural system. It has also been used with the name "tsatmades", in several old traditional and preservable buildings that are yet met in many regions of Greece, Turkey and other Balkan countries (Figure 1).

In this structural system the walls are composed by a wooden skeleton in the form of a usual braced-frame or truss structure, with vertical, diagonal and horizontal beam-like elements, that is filled with brick-masonry or stone-masonry with (or without) mortar, or just mortar alone. The joint connections of the wooden elements are rarely implemented with steel plates and mortises, and more often with solitary nails or rows of nails. A detailed description of this structural system is done in [1], but there isn't any other analysis suggested that could be helpful for the calculation of their stress state and bearing capacity. It is evident that static behavior of the truss-work is characterized by the development of axial forces (mainly), as well as bending moments, while the contribution of the infilling material in the system's stiffness, strength, and stress distribution is remarkable in general.

The static activation of the infilled truss-works is not always completely straightforward and a priori obvious. The tensile bond strength of the mortar at the interface between infill and truss-work is low and unreliable in general, thus allowing only compressive (normal) and limited frictional contact stresses to develop, while penetration is prohibited and separation or slipping along any parts of this interface may occur. The actual contact area varies during the seismic loading of the structure, thus resulting in a nonlinear response, even in the case of linearly elastic material laws. Furthermore, additional non-linearities may be presented due to inelastic material behavior. Due to the complexity of this structural system, some researchers [2] have fully ignored the presence of the infilling material in the structural analysis of the system, while some others [3] have considered the contribution of the infilling material by assuming a full bond at the interface between infill and truss-work. So, although there are plenty of studies concerning the static behavior of infilled frames ([4], [5], etc.), we have no knowledge of research works or codes that refer to a more precise structural analysis of the masonry infilled timber truss-works.

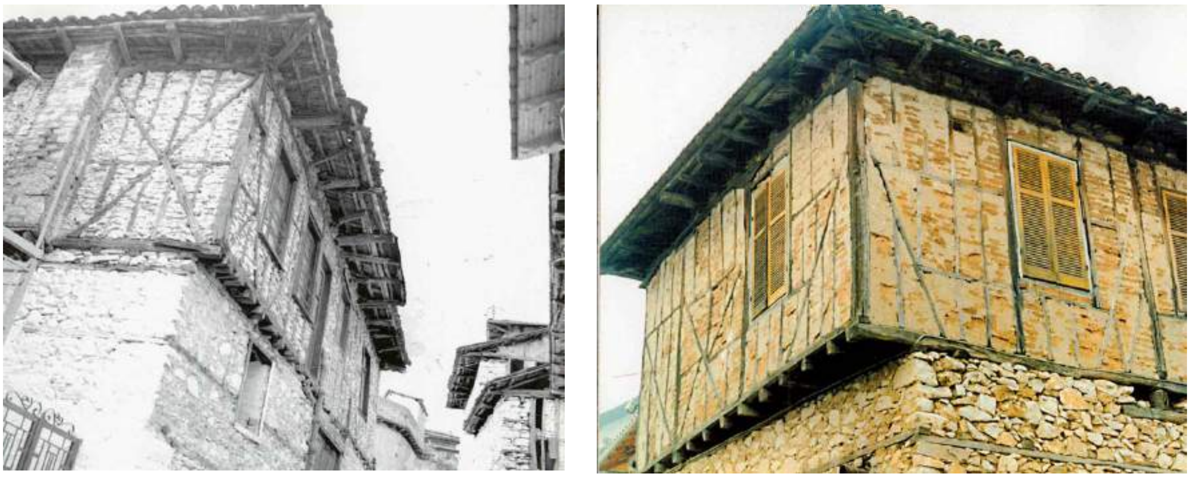


Figure 1. Old traditional buildings with load bearing walls made by "tsatmades"

In the present paper a proper detailed analytical finite element model (micromodel) for this structural system is formed and studied, which can describe with sufficient accuracy the static and dynamic (seismic) behavior of these walls, taking into account the aforementioned contact interface conditions. Numerical applications of the proposed model with comparisons to other suggested and often-used models are presented too.

2 ANALYTICAL MODELING

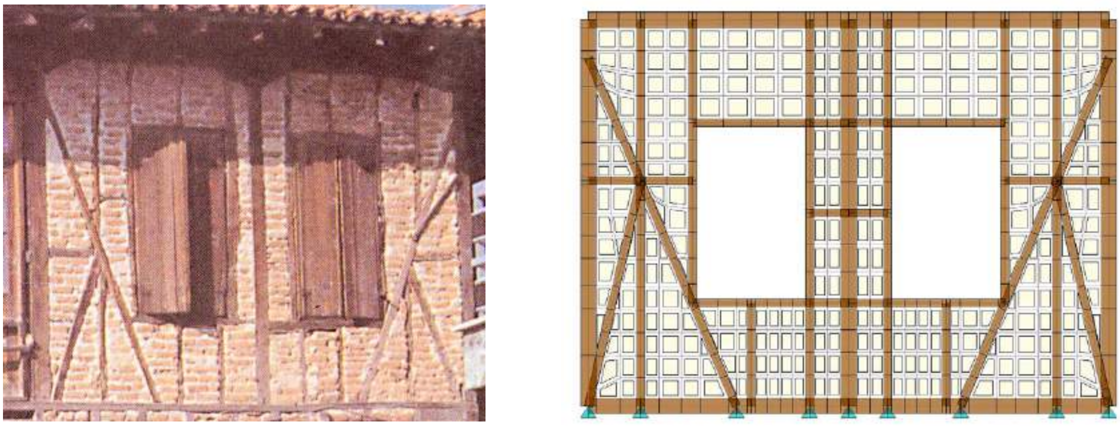
2.1 Description of the proposed model

A fine discretization mesh of finite elements is applied to the structural system under consideration, and a typical mesh of such a kind is shown in Figure 2 [6], which concerns the face wall of an existing old building.

In particular, the wooden elements of the truss-work are modeled with frame (beam-column) elements, the infilling masonry is modeled with plane-stress or shell elements, while for the joint connections of the frame elements, rigid or flexible link elements (springs) with finite size can be used.

The discontinuities along the length of the wooden parts and within their joint connections are modeled by using proper release-end conditions in the respective frame elements. For the proper consideration of the finite size of the frame elements' sections, rigid offsets between the neutral axis of the frame elements and the contact interface must be introduced.

The boundary conditions between the infilling masonry and the wooden elements are modeled with proper contact-friction bonds with Coulomb's law of dry friction [4]. Furthermore, elastic or inelastic constitutive laws can be used for the respective materials ([5]), as well as for the joint connections of the frame elements [2]. At this point, the significant role of the flexural stiffness of the frame elements must be emphasized; this means that the flexural stiffness must not be neglected, so that the contact interaction between the infilling masonry and the timber truss-work can be activated with certainty.



(a) (b)

Figure 2. (a) Face wall of an old building, (b) Respective analytical micromodel with finite elements

2.2 Contac interface conditions and solution procedure

If S_N and S_T are the normal and tangential (shear) force of the contact bond (tension positive), U_N and U_T are the corresponding relative end displacements (extension positive), $\delta S_N, \delta S_T, \delta U_N, \delta U_T$ are their incremental values and μ is the friction coefficient, these incremental values are subjected to the following constraints (2-D formulation [3]):

a. For initial conditions of separation $(U_N > 0)$, the incremental contact state is also separation, that is:

$$\delta S_N = 0, \quad \delta S_T = 0, \quad \delta U_N + U_N > 0 \tag{1}$$

b. For initial conditions of sticking contact $(U_N > 0, \quad \mu \cdot S_N + /S_T/ < 0)$, the incremental contact state is also sticking contact:

$$\delta U_N = 0, \quad \delta U_T = 0, \quad \mu(S_N + \delta S_N) + /S_T + \delta S_T/ < 0 \tag{2}$$

c. For initial conditions of slipping contact $(U_N > 0, \quad \mu \cdot S_N + /S_T/ = 0)$:
If $S_N < 0$, the incremental contact state may be either sticking contact (3a), or slipping contact (3b):

$$\delta U_N = 0, \quad \delta U_T = 0, \quad \mu(S_N + \delta S_N) + /S_T + \delta S_T/ < 0 \tag{3a}$$

$$\delta U_N = 0, \quad \delta U_T \cdot S_T \leq 0, \quad \mu(S_N + \delta S_N) + /S_T + \delta S_T/ = 0 \tag{3b}$$

If $S_N = 0$, the incremental contact state may be either sticking or slipping contact (relations 3a, 3b), or separation, that is:

$$\delta S_N = 0, \quad \delta S_T = 0, \quad \delta U_N \geq 0 \tag{3c}$$

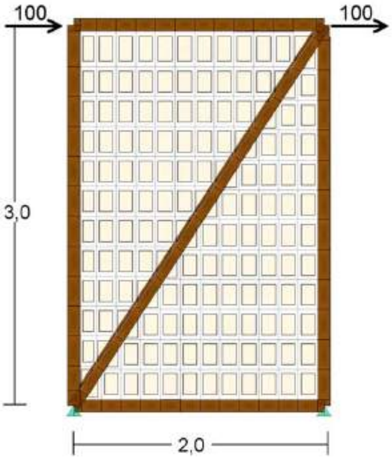
It is noted that the tangential relative displacements U_T are reversible for the separation state and irreversible for the slipping contact state. In certain existing computer programs for non-linear structural analysis, the above mentioned contact incremental constraints can be modeled approximately by using proper gap elements.

For the solution of the resulting mathematical problem with all the aforementioned non-linearities, standard nonlinear time-history methods of static or dynamic analysis can be applied (combination of the step-by-step and iterative methods). Within the framework of the present study, the analysis and solution capabilities of the computer programs SAP2000 [8] and ADINA [9] have been used.

3 APPLICATIONS TO SIMPLE WALLS WITHOUT OPENINGS

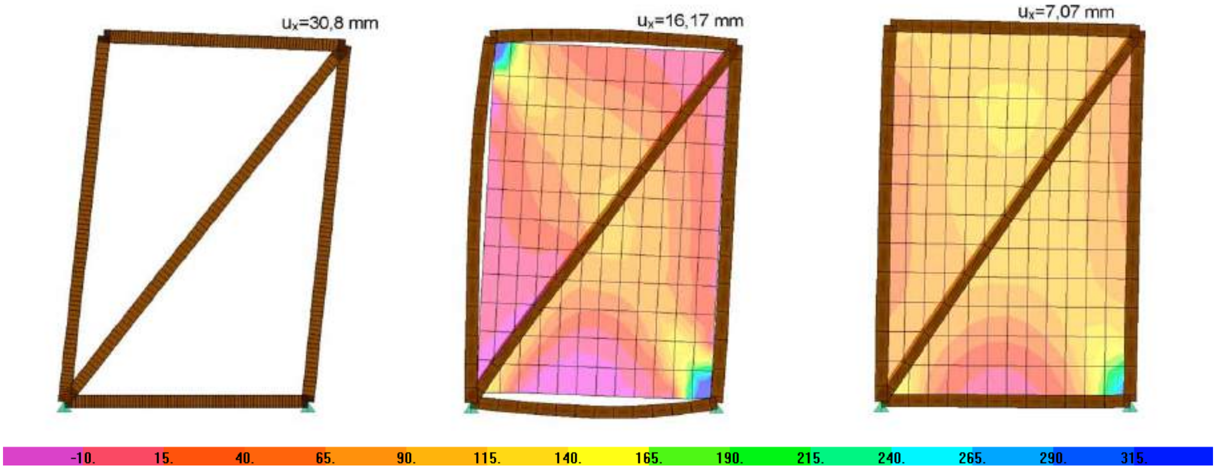
In the applications that follow, a proportionally increasing quasi-static horizontal load with a maximum amplitude of P=100 kN is applied at the top corners of the examined walls and the response values of the system are calculated. For each application the following 3 alternative models are formed and compared:

- model1: the proposed micromodel with contact interface conditions between truss-work and infilling
- model2: the respective bare truss-work model (without infilling)
- model3: a micromodel similar to model1, but with full bond at the interface of truss-work and infilling.



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 section: 10×10 cm
Infilling:	Isotropic $E=3\times10^6$ kN/m^2 $G=1,2\times10^6$ kN/m^2 Thickness: t=10 cm
Interface:	Friction coefficient μ=0,50

Figure 3. Micromodel of a rectangular (1×1)–span infilled truss-work with single diagonal bracing



(a) model2 (b) model1 (c) model3

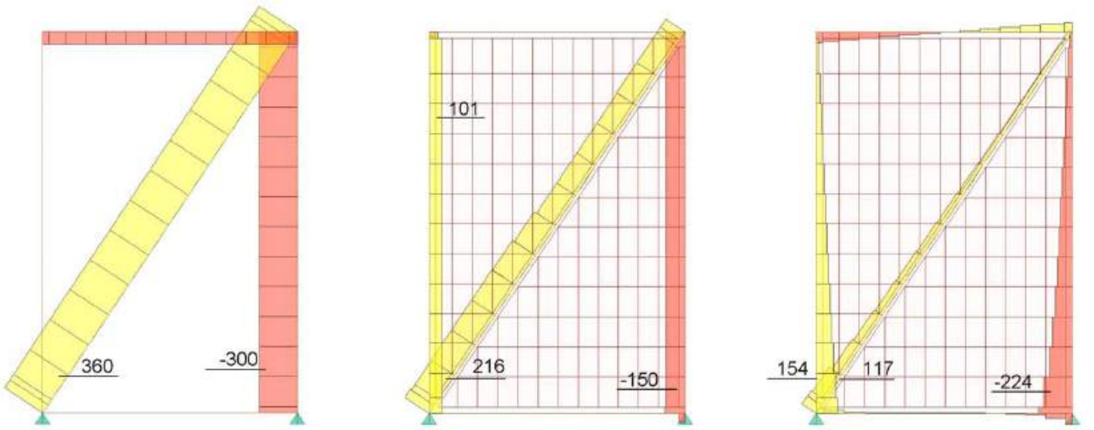
Figure 4. Deformed shape of the wall shown in Figure 3 and distribution of shear forces within infilling.

3.1 Rectangular 1×1–span truss-work with single diagonal bracing

The examined wall [7] and the respective discretized model are shown in Figure 3, together with the material and section properties of the structural members. For a more consistent comparison with the results of model2 (bare truss-work) the assumption of linear elastic behavior of all the materials is made, although this assumption is realistic only for small values of the applied horizontal load. Zero-size joints (without link elements or springs) are considered at the nodal connections of the frame elements, with release-end conditions (for zero bending moments) at the ends of these elements. The proposed model1 includes 72 frame elements, 156 shell elements and 78 gap elements.

Figure 3 shows the deformed shape of the wall and the distribution of shear forces within the infilling masonry. In the proposed model1 the separation areas between the infilling and the truss-work are clearly shown. The horizontal displacement at the top-right corner of the simplified model2 is 90% larger than in model1, while in the simplified model3 is 56% smaller than in model1. Regarding the distribution of shear forces, in model1 there is a high concentration at the compressive top-left and bottom-right corners of the infilling, and a formation of a respective diagonal zone with high shear forces which can be related to the well-known compressive diagonal strut of the infilled frames. In model2 the shear forces are substantially smaller and the formation of a diagonal zone with high shear forces is not so distinct.

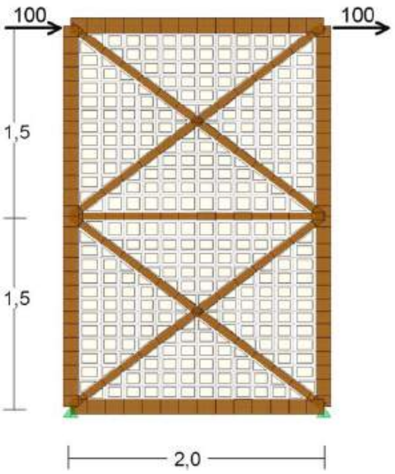
Figure 4 shows the axial force diagrams of the truss-works of the examined models. The divergence of the extreme axial forces, with respect to model1, range from 86% to 100% in the case of model2 and from -46% to 50% in the case of model3. It is obvious that all the results of both simplified models are very different than those of the proposed model1.



(a) model2 (b) model1 (c) model3

Figure 5. Axial force diagram in the truss-work of the wall shown in Figure 3.

3.2 Rectangular 1×2–span truss-work with double diagonal X-bracing



Wood: E=12×10^6 kN/m^2
G=4,61×10^6 kN/m^2
Column sections: 12×12 cm
Beam sections: 12×12 cm (top-bottom)
Beam sections: 12×6 cm (middle)
Diagonal sections: 12×6 cm

Infilling: Isotropic
E=6×10^6 kN/m^2
G=2,4×10^6 kN/m^2
Thickness: t=12 cm

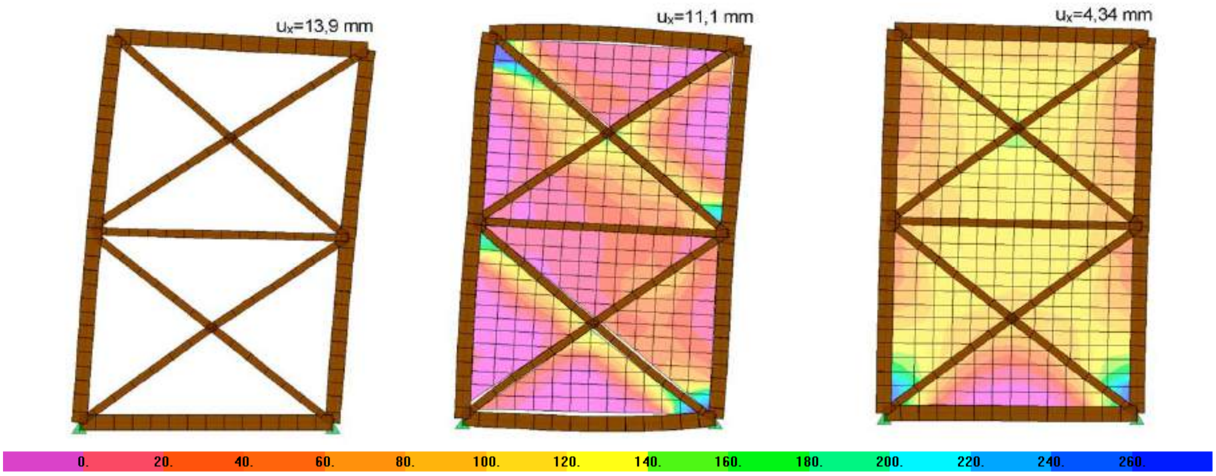
Interface: Friction coefficient μ=0,50

Figure 6. Micromodel of a rectangular (1×2)–span truss-work with double diagonal bracing

The proposed micromodel of the examined wall [6] is shown in Figure 6, together with the material and section properties of the structural members. In this model the diagonals have half the section height (12×6) than the other elements (12×12), while the values of the Young modulus E and the shear modulus G of the infilling masonry are twice larger than those in the previous application. As before, the assumption of linear elastic behavior of all the materials is made, and zero-size joints (without link elements) are considered at the nodal connections of the frame elements. Release-end conditions (for zero bending moments) are considered at the ends of the beams and diagonals, while the continuity of the columns in the middle of their height is retained. The proposed model1 includes 178 frame elements, 336 shell elements and 216 gap elements.

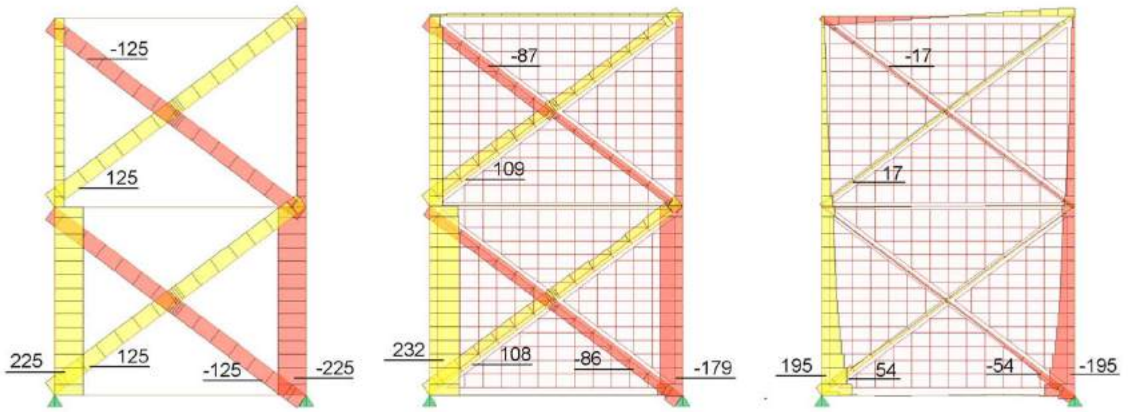
Figure 7 shows the deformed shape of the wall and the distribution of shear forces within the infilling masonry. With respect to the proposed model1, the horizontal displacement at the top-right corner of the simplified model2 is 25% larger, while in the simplified model3 is 60% smaller. In Figure 7b a concentration zone of the shear forces is observed along the two shortened diagonals (from up-left to down-right) of model1, which take their maximum values near the ends of these diagonals. Also the separation areas between the infilling and the truss-work are clearly shown. In Figure 7c the shear forces of model3 have a smoother distribution than in model1, while any diagonal zone with shear concentration cannot be observed.

Figure 8 shows the axial force diagrams of the truss-works of the examined models. The divergence of the axial forces of model2, with respect to model1, ranges from –3% to 26% for the columns, is about 15% for the tensile diagonals and about 44% for the compressive diagonals. The respective divergence of model3 ranges from –16% to 9% for the columns, is up to –84% for the tensile diagonals and up to 80% for the compressive diagonals. In conclusion, the simplified model2 provides a better estimation of axial forces than model3.



(a) model2 (b) model1 (c) model3

Figure 7. Deformed shape of the wall shown in Figure 6 and distribution of shear forces within infilling.

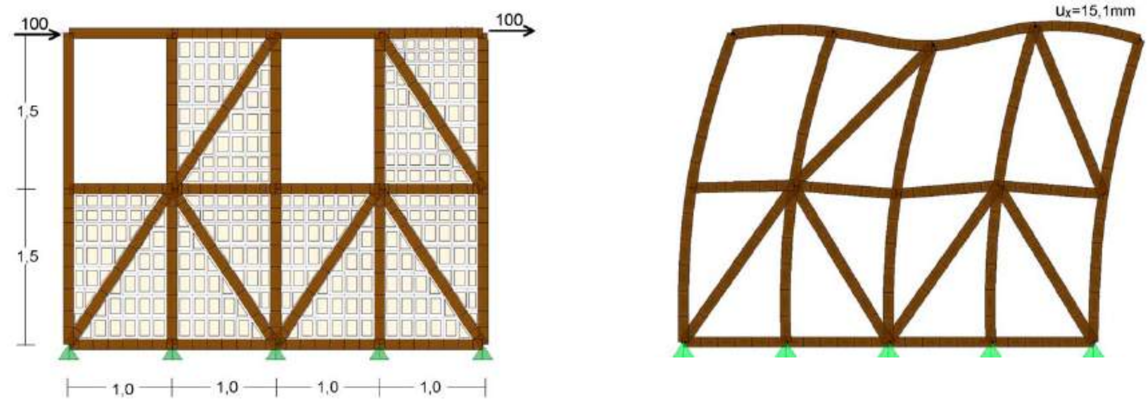


(a) model2 (b) model1 (c) model3

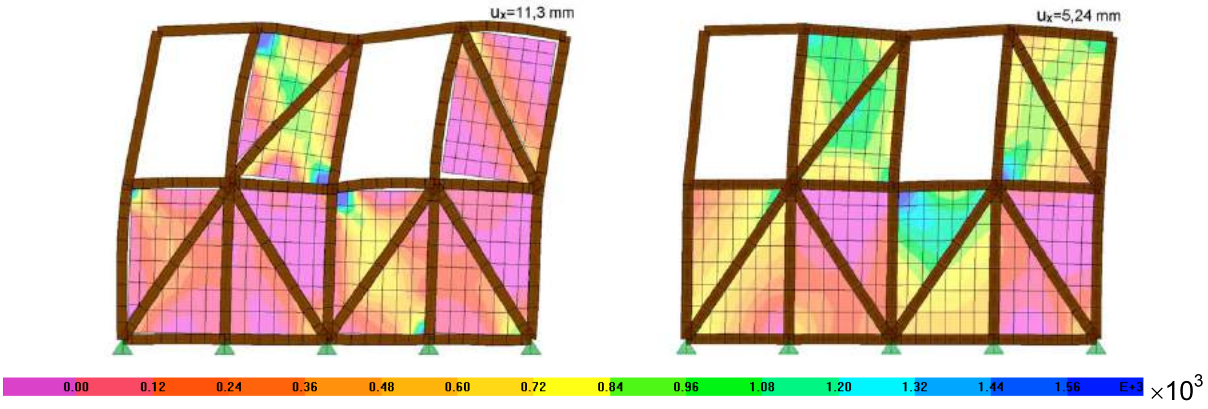
Figure 8. Axial force diagram in the truss-work of the wall shown in Figure 6.

4 APPLICATION TO A COMPLEX WALL WITH OPENINGS

The examined wall [7] in this application represents the entire face of a small building’s storey. The proposed model1 is shown in Figure 9a, and the material and section properties of the structural members are shown in Table1. As previously, two additional simplified models (model2 and model3) are formed and compared.



(a) (c) model2



(b) model1 (d) model3

Figure 9 (a): Discretization of the examided wall, (b) (c) (d): Deformed shape and distribution of shear streses within infilling of the wall shown in (a).

Wood	Infilling masonry	Interface
$E = 12\times10^6$ 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	Isotropic $E = 3\times10^6$ kN/m^2 $G = 1{,}2\times10^6$ kN/m^2 Thickness: t=10 cm	Friction coefficient: μ=0,50

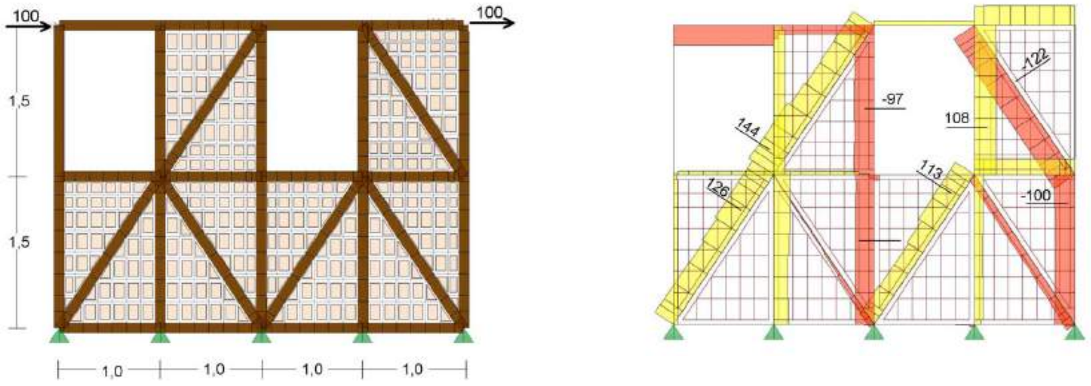
Table 1. Material and section properties of the examined wall with openings.

The assumption of linear elastic behavior is made for all the materials, and zero-size joints are considered at the nodal connections of the frame elements. All the columns have a 3,0 m continuous length, the top and bottom beams have a 4,0 m continuous length, while release-end conditions (for zero bending moments) are considered at the ends of the 6 diagonals and the 5 beams in the middle of the storey's height. The proposed model1 includes 234 frame elements, 294 shell elements and 266 gap elements.

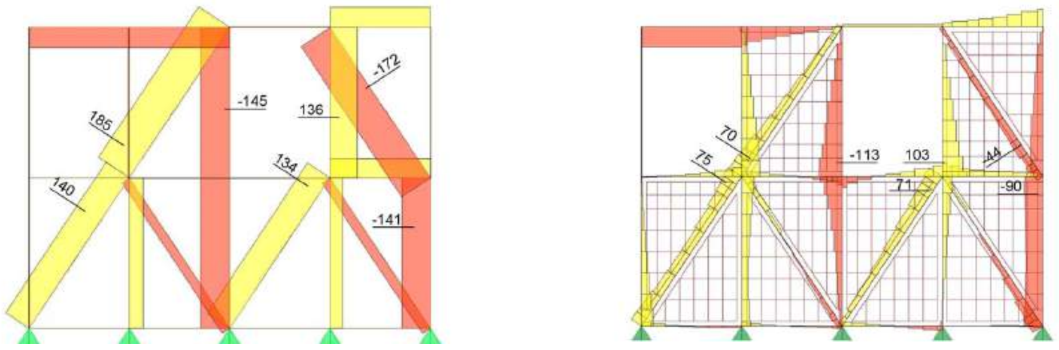
Figures 9b, 9c and 9d show the deformed shape of the examined models and the distribution of shear stresses within the infilling masonry. In the proposed model1 the separation areas between infilling and truss-work are clearly shown. With respect to the proposed model1, the horizontal displacement at the top-right corner of the simplified model2 is 34% larger, while in the simplified model3 it is 54% smaller.

In Figure 9c diagonal zones with shear concentration can be observed in all the 3 shortened diagonals of model1, where truss elements do no exist. In Figure 9d the shear forces of model3 have a smoother distribution than in model1, while less distinct diagonal zones with shear concentration can be observed at the upper level of the wall along the shortened diagonal (on the left), as well as along the lengthened diagonal (on the right).

Figures 10b, 10c and 10d show the axial force diagrams of the truss-works of the examined models. The divergence of the axial forces of model2, with respect to model1, is up to 26% for the most tensile elements and up to 49% for the most compressive elements. The respective divergence of model3 is up to -51% for the most tensile elements and up to -64% for the most compressive elements. In conclusion, the simplified model2 provides a better estimation for the axial forces than model3, especially for the most tensile elements.



(a) (b) model1



(c) model2 (d) model3

Figure 10 (a): Discretization of the examided wall, (b) (c) (d): Axial force diagram in the truss-work of the wall shown in (a).

5 CONLUSIONS

The methodology of the micromodels with contact interface conditions provides increased analysis capabilies for a more detailed and accurate study of the stress, strain and available strength of the masonry-infilled timber truss-works. In the writers opinion, the uncertainties of the material laws, the joint connections and the construction details of these walls in general, affect much more the results of the system's response than the inevidable imperfections of the proposed micromodels. However it is not yet efficiently applicable in large structural systems like an entire building.

Regarding the examined simplified models, it must be noted that, depending on the form of the diagonal bracing, these models may give very inaccurate results. It must be noted also that the simplified model of the bare truss-work without infilling provided better results than the simplified model with full-bond interface conditions.

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