THE GLOBAL PERFORMANCE OF URM BUILDINGS UNDER HORIZONTAL ACTIONS BASED ON NUMERICAL MODELLING

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ABSTRACT

The response of unreinforced masonry structures under horizontal actions like earthquakes or wind has a unique behaviour which differs significantly from the response of other structural systems such as reinforced concrete. This unique behaviour is caused mainly by the high stiffness, brittle material behaviour, and the deformability of the slab system. While, it is common to segment the structure into components to extrapolate out component behaviour and to predict overall structure response, such an approach may neglect important global effects which can result in significant influences. The work focuses on the interaction between masonry structure elements and their influences on the global behaviour. Numerical models based on the discrete / finite element approach of different scales have been built for a typical European masonry terraced house. The numerical models were verified and calibrated with full scale tests performed within the frame of the European research project ESECMaSE. The models have been used to investigate the contribution of each shear wall to the overall capacity of the structure, and to determine the portion of vertical / horizontal loads carried by each wall. The results give an insight into the interaction between the deformation of the slab and the rocking of the shear walls, and show that the slab deformation will significantly influence the vertical load distribution on the shear walls. To neglect the influence of vertical load distributions, strip models were considered. A comparison of the results of the strip model with the results of the global model shows that the strip model results are on the safe side.

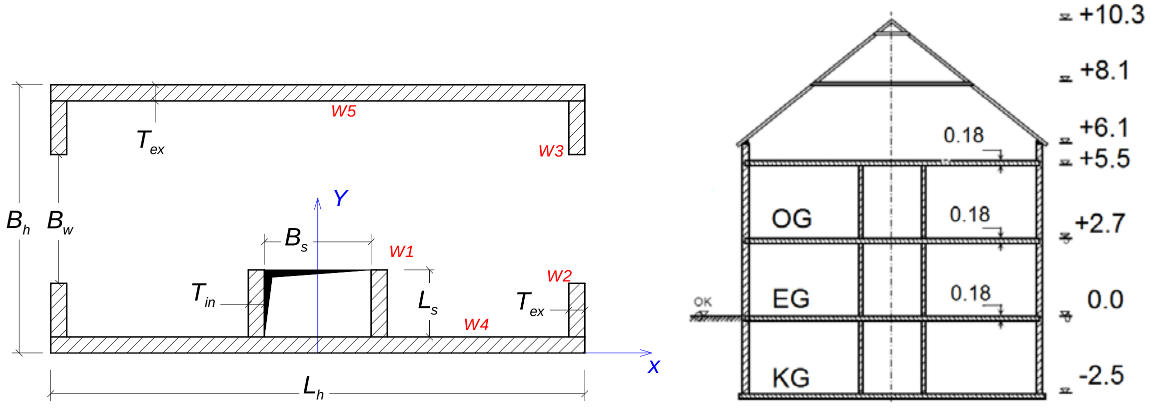
KEYWORDS: discrete-finite element method, global structure behaviour, earthquake, wind, masonry stiffening walls, strip models

INTRODUCTION

The response of masonry structures under horizontal loads has a unique behaviour that differs significantly from the response of other structural systems such as reinforced concrete. This unique behaviour is mainly caused by the high stiffness and brittle material behaviour exhibited by masonry and the deformability of the diaphragm system. While, it is common to segment the structure into components to predict overall structure response, such an approach may neglect important global effects which can result in significant influences.

Some experimental studies were performed in that direction on the global response of masonry building under horizontal actions. In Ljubljana, the global behaviour of apartment buildings were investigated by shaking table tests of 1:5 scaled specimens (Tomaževič / Weiss [1]). In the USA, several investigations were made on the seismic performance of masonry structures with flexible diaphragms (Moon [2]). In Europe, comprehensive investigations were carried out on earthquake resistance of masonry structures within the framework of the European Union research project ESECMaSE (Meyer / González [3]). True scale pseudo-dynamic tests have been performed on two terraced house halves with a typical central European ground plan.

The developing of engineering models that describe the overall response of masonry buildings under horizontal loading has received considerable interest. Ötes / Löring [4] have proposed a bar model that considers the coupling of the bar system of the inner and outer shear walls to ensure the compatibility of deformation. The gable walls were included in the model as vertical bars. The external walls develop a frame action, which discharge some of the loads coming to the inner walls. However, it was assumed that there were generally uncracked cross sections. Elsche [5] has performed finite element analyses for a terraced house under horizontal displacements. The model considers masonry walls from calcium silicate with thin layer mortar. The walls were assumed to have cohesion contact with the slab, so that the possible opening failures can be simulated. The external walls have been separated without considering contact in between; contact elements were only defined on the interfaces between the slab and the wall. The results of calculation show the contribution of each shear wall from the whole basement shear force. Fehling / Stürz [6] have used a bar model with attached rigid bodies in double-T form for modelling the shear walls in the case of rocking. According to Fehling / Stürz [6], the rocking occurs by meeting a specific criterion based on normal stress, compression strength of masonry, and the ratio of length to the height of the wall, which is quite possible in the case of the terraced house, mainly due to the low normal forces. The combined work of the shear wall with its flange has been investigated within a research project by Zilch et al. [7], [8]. Several tests on full-scale walls with a T-shape and different execution detailing (e.g. the connection between the shear wall and intersecting wall was made using shear ties or interlocking) under combined loadings (static-cyclic and pseudo-dynamic) have been performed. Concerning the load bearing capacity and the stiffness characteristics of shear walls, the study showed significantly better behaviour under combined shear loadings, compared to single walls.



(a) (b)

Figure 1: Typical terraced house: a) the layout in ground floor showing the notation of dimensions and walls; b) cross section along the y axis

In the present contribution, the performance of a masonry building under horizontal loads has been investigated based on understanding the response of the global system and the interaction between its components. The terraced house, a typical central European residential building, is considered as a reference masonry building (Figure 1 and Table 1). This building has been considered in many research works ([9], [3], [10], [4] and [5]) as it helps to investigate the performance of the masonry building in its simplest form. Three models for the reference building with different accuracy levels and modelling approaches are considered: (1) Discrete / finite element model on a unit level, (2) Discrete / finite element model on a wall level, and (3) Strip model.

Table 1: Dimensions of the typical terraced house masonry building

L_h = 10.0 [m]	Length of the house
B_h = 5.0 [m]	Width of the house
B_w = 2.4 [m]	Width of the window opening
B_s = 2.0 [m]	Width of the staircase
L_s = variable [m]	Depth of the staircase
T_{ex} = 30.0 [cm]	Thickness of the external walls
T_{in} = 17.5 [cm]	Thickness of the internal walls

DISCRETE/ FINITE ELEMENT MODEL ON A UNIT LEVEL – MODEL 1

This model has been built with the intention to get an insight into the global response of the building, the interaction between the structure components, the distribution of horizontal forces, and the damage progress within the structure up to the point of collapse. The applied horizontal load has been linearly increased in order to explore any existing potential reserves.

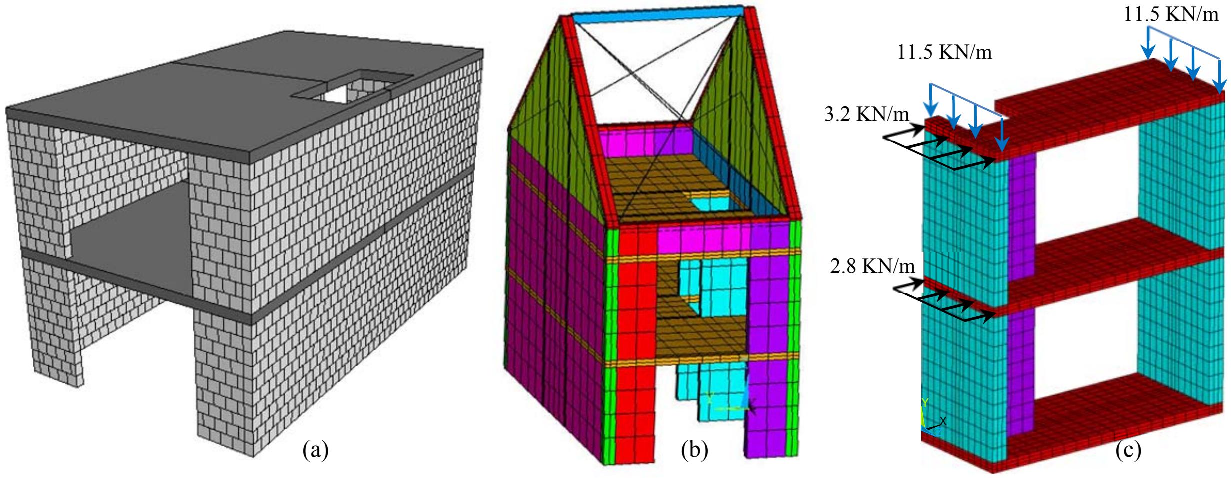


Figure 2: Discrete / finite element model of the terraced house: a) on a unit level in LS-DYNA; b) on a wall level in ANSYS - the slab modelled also as a discrete element; c) strip model - the walls considered as discrete elements (Jäger et al. [9]).

In this model, the finite element mesh is continuous on the unit level, while tied contacts with defined failure criterion for tension and shear can be detected between individual masonry units

(Figure 2-a). The slabs are modelled as discrete elements which supported on walls by contact elements. The principles of modelling and material parameters can be found in [10]. Transient calculation has been performed based on explicit integration approach by LS-DYNA code.

DISCRETE / FINITE ELEMENT MODEL ON A WALL LEVEL – MODEL 2

This model is simpler than the pervious one, but shows efficiency for parametric study without dropping the capability to describe the global behaviour, including the rocking failure of the walls, and the interaction and influences of different components (Figure 2-b). The model has been built in ANSYS within a research project to develop an engineering model for masonry shear walls (Jäger et al. [9]). Each wall has been considered as separate discrete element, which is in contact with the other slabs/walls. Unidirectional frictional contact elements have been defined on the interfaces between the discrete elements, so that the shear walls were connected through frictional contact elements to the long walls. This was done to ignore the transfer of tensile forces between the adjacent walls, which might be connected by flat steel anchors. The material was assumed to be elastic within the discrete elements and cracks were only possible on the interfaces between the discrete elements. Static calculations have been performed for this model under different load combinations (Table 2), and different material combinations (Table 3). The horizontal actions applied as wind loads on the house were as follows: the wind pressure on the front wall was 0.4 KN/m^2 and the suction on the opposite side was 0.25 KN/m^2. In Table 3, the values for the clay bricks are based on the gross sectional area. The different elastic modulus values were decreased following the investigations of Hannawald / Brameshuber [11]. Parametric study has been performed for the variation of the length of the inner wall using L_s =1.25, 1.50, 1.75 and 2.00 m.

Table 2: The considered load combinations

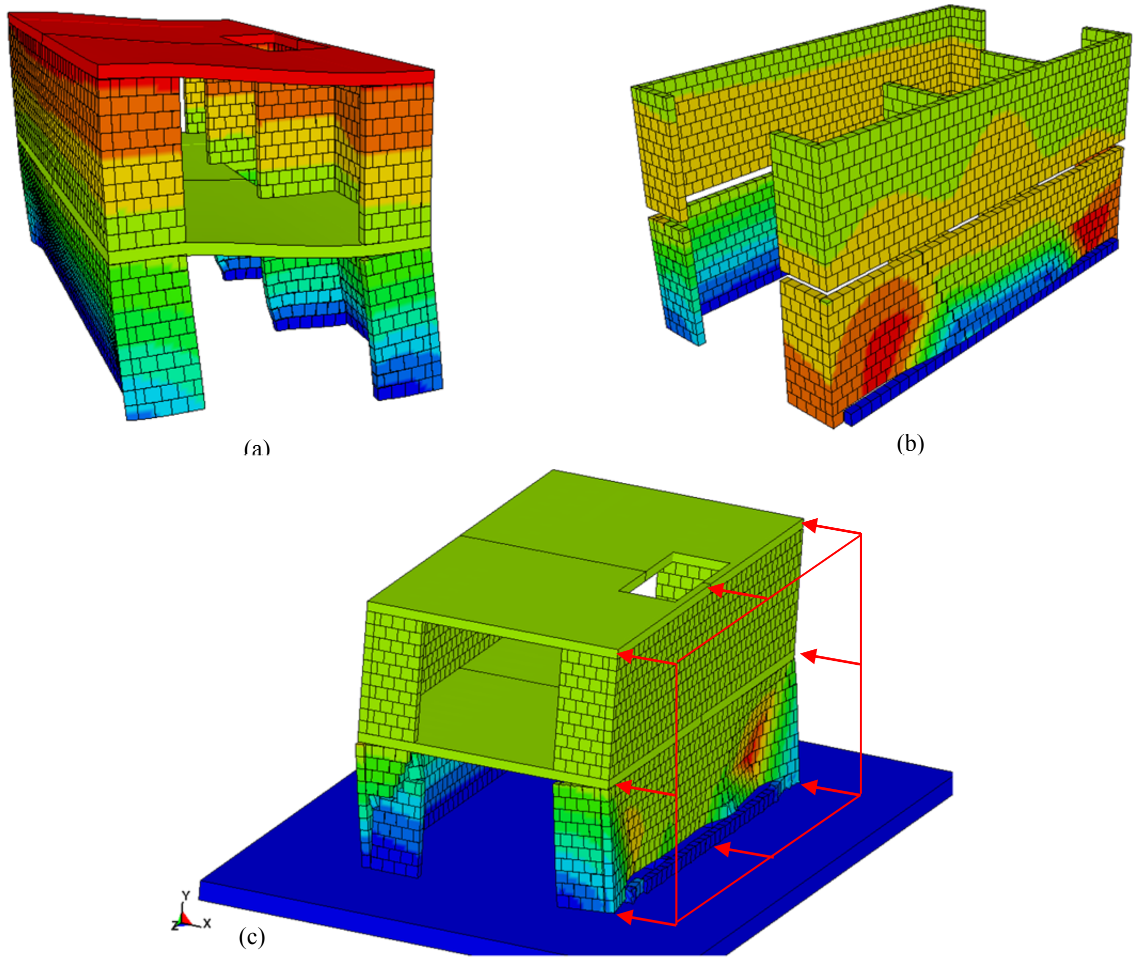
1	Dead Load
2	Dead Load + Wind Load in Direction Y+
3	Dead Load + Wind Load in Direction Y-

Table 3: Orthotropic material properties the house masonry walls

Material properties	External Walls		Internal Walls
	Front side HLz6/LM21	Gabel HLz6/LM21	HLz12/NMIIa
E	2420 [N/mm^2]	2420 [N/mm^2]	5500 [N/mm^2]
E_x	0.277 × E [N/mm^2]	0.277 × E [N/mm^2]	0.277 × E [N/mm^2]
E_y	0.550 × E [N/mm^2]	0.550 × E [N/mm^2]	0.550 × E [N/mm^2]
E_z	1.000 × E [N/mm^2]	1.000 × E [N/mm^2]	1.000 × E [N/mm^2]
G_{xy}	0.050 × E [N/mm^2]	0.050 × E [N/mm^2]	0.050 × E [N/mm^2]
G_{xz}	0.209 × E [N/mm^2]	0.209 × E [N/mm^2]	0.209 × E [N/mm^2]
G_{yz}	0.378 × E [N/mm^2]	0.378 × E [N/mm^2]	0.378 × E [N/mm^2]
ν_{xy}	0.140	0.140	0.140
ν_{xz}	0.100	0.100	0.100
ν_{yz}	0.100	0.100	0.100
Density	9.000 [KN/m^3]	9.000 [KN/m^3]	9.000 [KN/m^3]

STRIP MODEL – MODEL 3

The strip model decouples the in-plane behaviour of the shear wall within the structure from any transversal effects. It helps to separate the influence of the force distribution from the overall behaviour and is capable of describing the interaction between the shear wall, the flange wall and the slab. Several experimental and numerical studies have used the strip approach to explore the performance of masonry buildings under horizontal actions. Some shaking table tests of strip specimens were executed within the frame ESECMaSE project [12]. The results of the tests provided a clear explanation for the in-plane performance of the strip. In [10] a strip model has been built based on the approach described for model 1 and the results from ESECMaSE project were used to check the validation of the model. Löring [13] has performed numerical modelling of strips of different patterns considering the possible arrangements of walls in masonry buildings. The same modelling principles of model 2 have been used for the strip model. The considered strip in this study has been chosen to include one of the inner shear walls of the single terraced house with an effective flange length calculated according to EC6 [14] (Figure 2-c).



(a)

(b)

(c)

Figure 4: Damage progress under horizontal loads up to collapse: a) the initial failure - opening of the slab due to the rocking of the shear walls; b) tensile horizontal cracking of the flange wall which is caused by the uplifting of the slab; c) the failure of the shear walls and collapse mechanism of the structure.

DAMAGE PROGRESS UNDER HORIZONTAL LOAD

The results obtained from the detailed model 1 can give an insight into the damage progress within the structure. The structure has been subjected to linearly increasing horizontal wind pressure and the damage events have been observed. In general, the progression of damage was influenced by the rocking of the shear walls. However, the simulation shows three important events: (1) separation between the slab and shear wall due to the rocking of the shear walls; this starts at an early loading stage, (2) tensile horizontal cracking of the transversal shear wall due to uplifting of the slab, and (3) failure of the shear wall which is affected basically by the early failure in the adjacent transversal wall, and immediately follows the tensile failure of the transversal wall (Figure 4).

The progression of damage within the structure imposes a specific distribution of forces after each damage stage. During the uplift of the slab, most of the vertical loads which are transmitted to the flange walls are going to be transmitted to the shear walls. This causes an increasing level of vertical stresses in the shear walls, and, thus, a change in the shear wall capacities, and in the horizontal load distributions. Several important behavioural aspects can be observed in the simulation of the damage progress, which could help to improve the capacity of the structure as whole. Significant flange participation has been observed. The primary contribution of the observed flange participation increases the applied vertical load in the shear walls. Significant portions of the flange walls were engaged due to the uplift associated with local shear wall rocking as well as the global rocking.

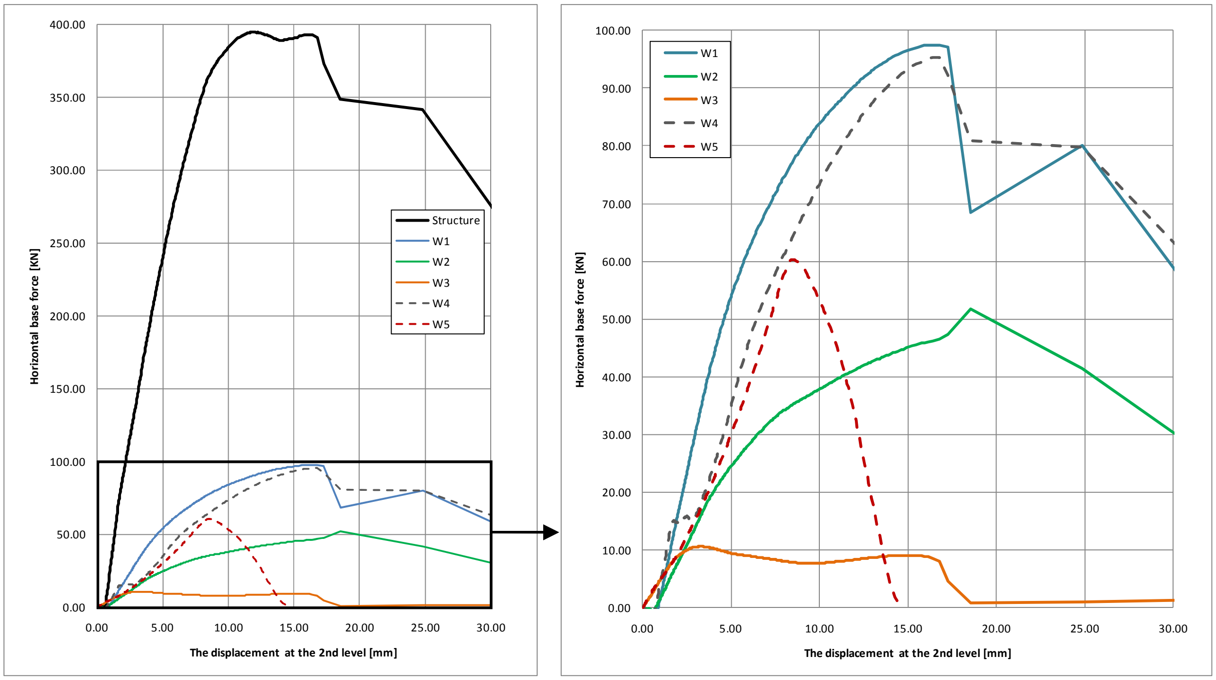


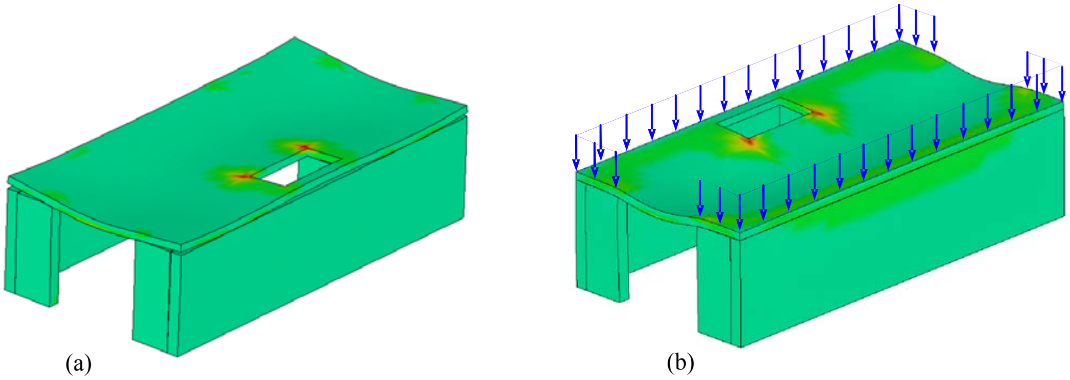
Figure 5: Capacity curves for masonry walls; the capacity curves of flange walls are dashed.

DISTRIBUTION OF THE HORIZONTAL LOADS

The distribution of the horizontal loads plays an important role in the design of the shear walls. The available approach in engineering practice is to distribute the horizontal forces to the shear walls proportional to their stiffness. This is correct in the elastic range, but, due to the way that damage develops and the interaction between the structure components, this method is not realistic. In addition, the summation of the peak resistances of each single shear wall is not realistic, as it overestimates the load bearing capacity of the structure. Figure 5 shows the capacity curves of the walls, which are defined as the relation between the base shear force and the displacement at the second level. Each capacity curve has its peak at specific displacement. The capacity curves in Figure 5, which are obtained from the interaction of all structure components, differ from the capacity curves of single shear walls. The capacity curves of flange walls demonstrate considerable participation to the overall structure capacity.

DEFORMATION OF THE SLAB AND ITS INFLUENCE ON THE TRANSMISSION OF VERTICAL LOADS

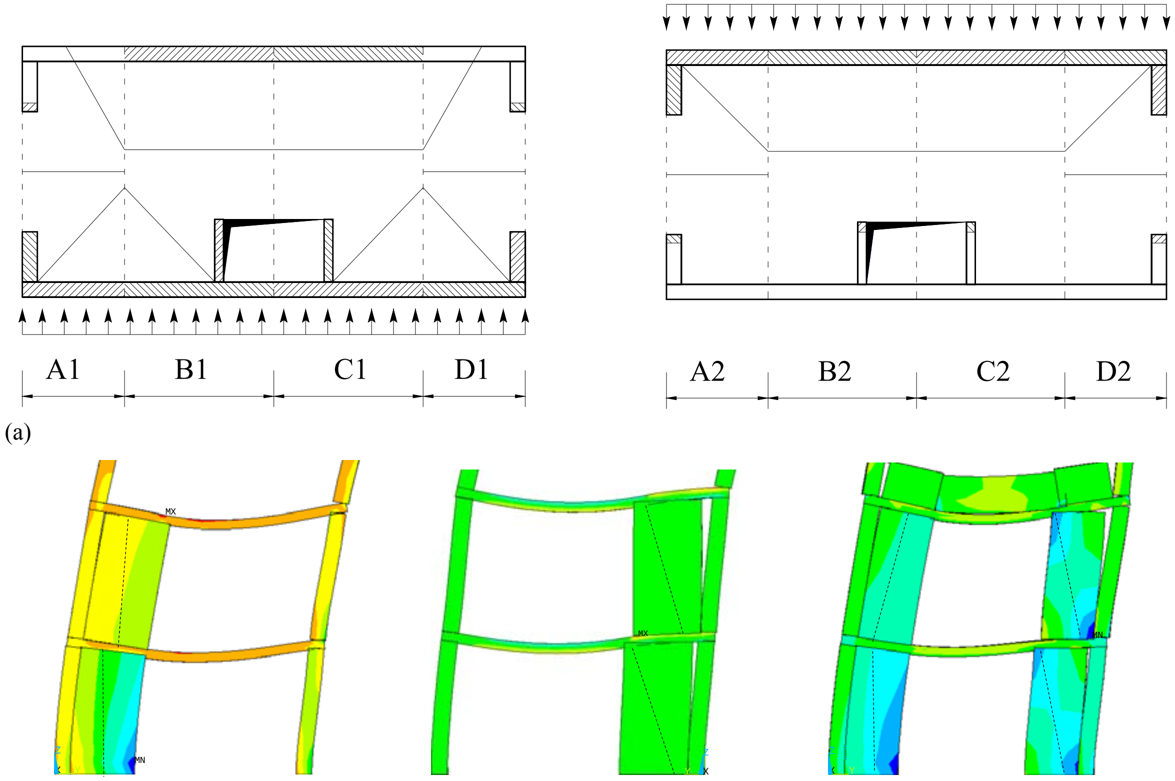
The vertical load transferred to the shear wall plays an important role in the load bearing capacity against horizontal actions. The traditional design methods in engineering practice don't consider the influence of slab deformation to determine the vertical actions on the walls, but are based on dividing the area of the slab into influence areas which depend on the geometrical distribution of the shear walls; examples for that include: DAfStb Heft 240 (Grasser / Thielen [15]), and the procedure of MINEA software described in (Mister [16]). Figure 6 shows the deformation of the slab under different loading conditions and the variation of load transmission areas under different loading conditions. Slab deformations basically depend, on one hand, on the applied loads and, on the other hand, on the interaction with the supporting walls. This confirms the importance of the contribution of vertical loads transmitted by the gable walls into the overall load bearing capacity.


(a)

(b)

Figure 6: The influence of the applied vertical loads on the load transmission areas: a) the deformation of the slab under its self weight; b) the deformation of the slab under self weigh and uniform linear load on the perimeter of the slab.

The simulation results under horizontal loads are influenced basically by the rocking of the shear walls and deformation of the slab. Based on the direction of horizontal loads and the shear wall distribution, the slab-wall interaction behaviour can be explained by dividing the structure into specific strips (Figure 7-a). The slab-wall interaction is basically affected by the existing of consistency between the rotation of the slab and the rocking of the shear wall. In strips B1 and C1, (Figure 7-b) the slab is almost in full contact with the shear wall, with no opening of the slab due to the consistency between rotation of the slab and the rocking of the shear wall. In strips B2 and C2, (Figure 7-b) the slab opens due to the inconsistent rotation of the slab and the rocking of the shear wall. In strips A1, D1, A2, and D2 the slab deforms consistently with the left shear wall but inconsistently with right one. In case of consistency, the behaviour of the shear wall is almost similar to a cantilever with opposing moments and rotational springs on each level; however, in case of inconsistency, the cantilever model is conservative and cannot represent the quasi-hinged connection between the wall and the slab.

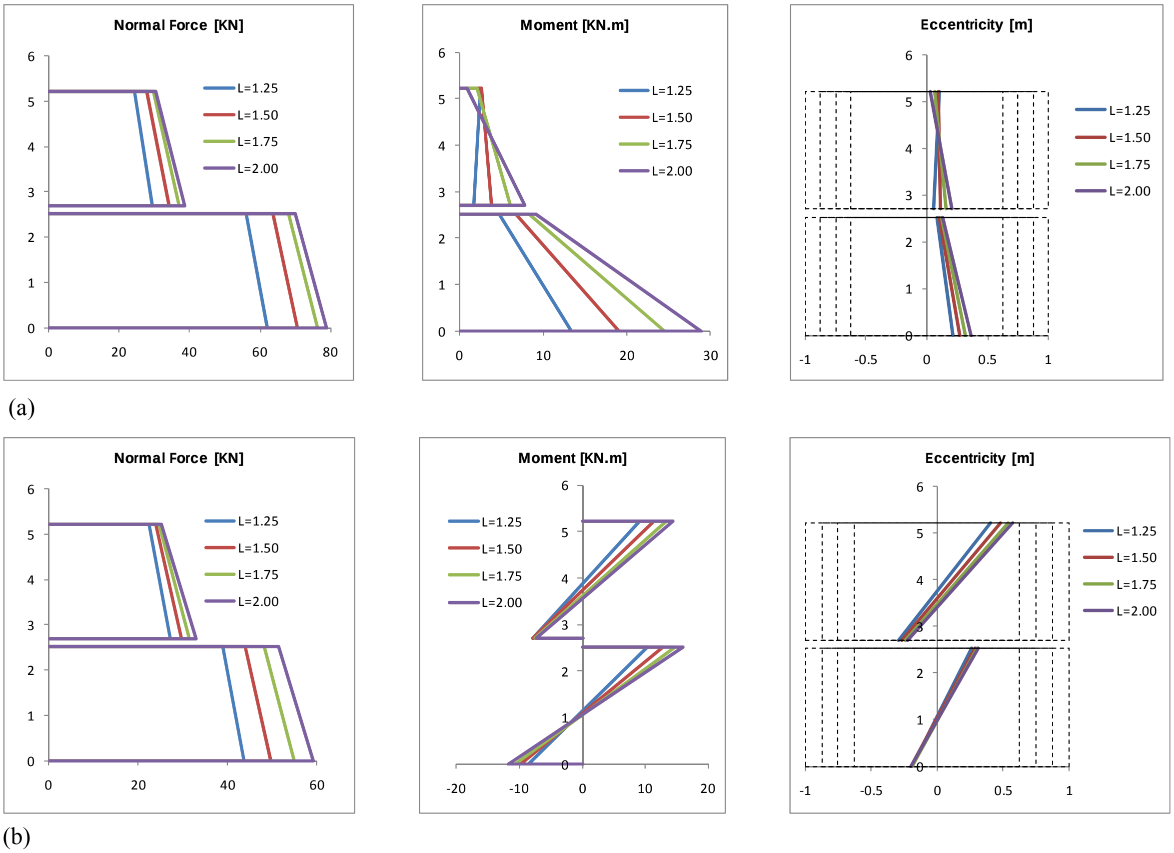


(b) Strips B1and C1 Strips B2 and C2 Strips A1, D1, A2, and D2

Figure 7: Deformation of the slab and its influence to the transmission of vertical loads: a) the influence of horizontal load direction on vertical load transmission areas; b) ANSYS model results for the responses of the strips from the global model.

INFLUENCE OF THE SHEAR WALL LENGTH

In previous section, it has been shown how the deformation of the slab influences the load flow through the shear walls and thus, the appropriate design model. However, this is also influenced the most by the shear wall dimensions, i.e. the ratio of length to the height of the wall. A shorter length of wall helps to produce rocking behaviour, and vice versa. The model 2 has been analysed for different lengths of inner shear wall (1.25, 1.50, 1.75, and 2.00 m). The internal forces of this wall are shown in Figure 8. The diagrams shown in Figure 8-a are corresponding to the case of consistent rotation of the slab with the rocking of the shear wall. The shape of moment diagram for a shear wall of length 2.00 m confirms that the cantilever model can be a good representation of this case. In case of inconsistency (Figure 8-b) there are not big differences in the shape of moment diagrams.



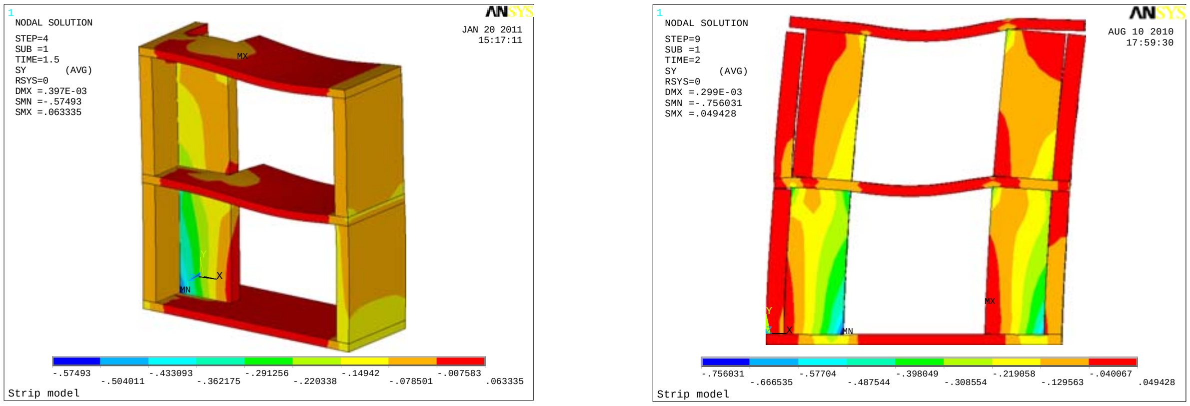
(a)

(b)

Figure 8: Influence of the inner shear wall length on the moment diagram; a) horizontal load is in positive direction of axis Y; b) horizontal load is in negative direction of axis Y.

COMPARISON THE STRIP MODEL WITH THE GLOBAL MODEL

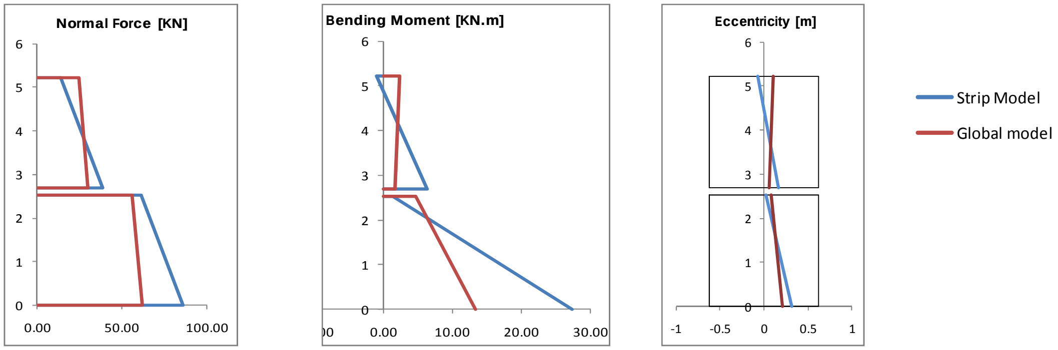
The results of the strip model give a clear explanation of the wall-slab interaction in the plane of the shear wall. Figure 9 shows the results of two strips models, one including the inner shear wall and the other including both external shear walls.



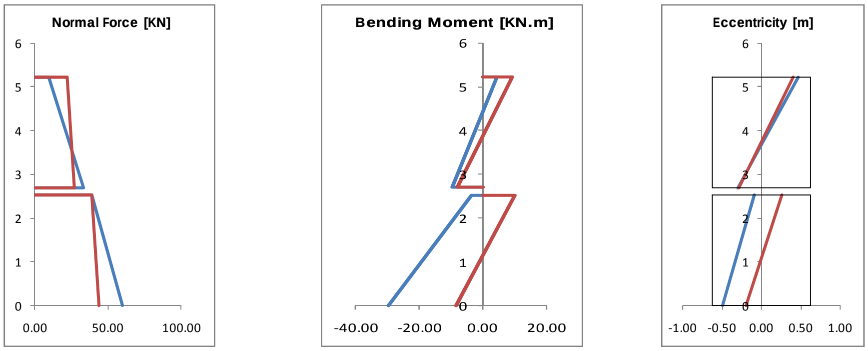
(a) (b)

Figure 9: Strip model FEM results; a) strip model for the inner shear wall in the terraced house; b) strip model for the external shear walls in the terraced house.

The vertical / horizontal portion of forces applied on the strip model has been calculated according to the traditional methods, i.e. the distribution of the horizontal forces calculated proportional to the stiffness of the shear walls. However, the calculation results in Figure 10 show that the strip model results are on the safe side of the global model results.



(a) Load Combination 2: Dead Loads + Horizontal load in positive direction of axis Y



(b) Load Combination 3: Dead Loads + Horizontal load in negative direction of axis Y

Figure 10: Comparison the internal forces between the strip model and global model

CONCLUSIONS

The global behaviour of a masonry terraced house subjected to horizontal loads has been investigated, with a focus on the interaction between the structure elements and their influences on the global behaviour. In general, the progression of damage has been influenced by the rocking of the shear walls. Significant flange participation has been observed. The primary contribution of the observed flange participation increases the applied vertical loads to the shear walls. The slab-wall interaction is basically affected by the existence of consistency between the rotation of the slab and the rocking of the shear wall. In case of consistency, the behaviour of the shear wall is almost similar to a cantilever model with opposing moments and rotational springs on each level; however in case of inconsistency, the cantilever model is conservative and cannot represent the quasi-hinged connection between the wall and the slab. The use of strip modelling shows capabilities to represent the in-plane behaviour of the slab-wall interaction. The results of the strip model lay on the safe side of the global model ones. The development of a hand calculation approach considering all the described behaviours is quite a challenging problem.

However, the adoption of the strip modelling approach through commercial software is reasonable.

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