Pushover analyses of mixed RC-URM wall structures

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LISBOA 2012

SUMMARY:
Following a re-evaluation of the seismic hazard in Switzerland, a country of moderate seismicity, the seismic design spectra have increased in the last revision (2003) of the Swiss building code. As a consequence, many new residential buildings are constructed using both reinforced concrete (RC) and unreinforced masonry (URM) structural walls instead of URM walls only. Despite the fact that such systems are also popular in other countries, there is a general lack of knowledge concerning the seismic behaviour of mixed RC-URM wall buildings. This paper presents the results of a numerical study on the global force-displacement characteristics of mixed RC-URM wall buildings, identifying the different responses of the structures considering various modelling approaches and mechanical assumptions for RC and URM elements. To this purpose, pushover analyses using different kind of modelling approaches were carried out. The obtained results are strongly dependant on the model chosen.

Keywords: mixed RC-URM wall structures, seismic behaviour, pushover analysis

1. INTRODUCTION

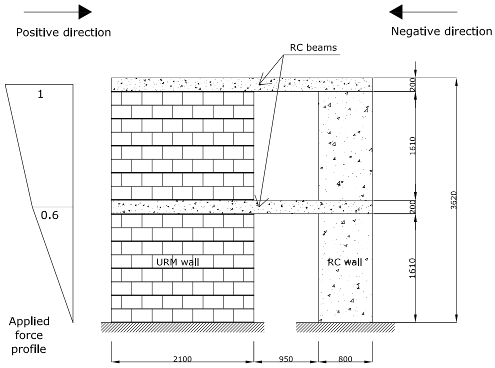
Many new residential buildings in Switzerland feature mixed constructions consisting of mixed reinforced concrete (RC) and unreinforced masonry (URM) structural walls coupled by RC slabs. A typical mixed reinforced concrete-unreinforced masonry wall structure is shown in Fig. 1a. Despite their popularity, there is a general lack of knowledge concerning their seismic behaviour and they are generally designed using over-simplified design assumptions. This paper presents the results of a study of the force-deformation characteristics of a mixed RC-URM wall system, considering various approaches and mechanical assumptions.

1.1. Model building

A two-dimensional two storey building, representative of mixed RC-URM wall structures, was considered in the current study. It is composed by a URM wall and a RC wall; both walls have a thickness of 150 mm. The two walls are connected by means of RC beams representing the effective width of the slab. According to Priestley *et al*. (2007), the effective slab width can be estimated as three times the thickness of the wall. A schematic diagram of the example structure is shown in Fig. 1b.

Force-deformation characteristics of the selected building are obtained by pushover analysis. Figure 1b shows the assumed force profile for the pushover analyses and the sign convention for the positive and negative direction of loading. All the pushover analyses were carried out applying a fixed force pattern. The response of the example structure depends upon the direction of loading as the structure is not symmetric. Due to the presence of the RC beams, the axial force of the URM wall decreases when the structure is subjected to loading in the positive direction; the axial force of the URM wall increases when the structure is subjected to loading in the negative direction.


a



b

Figure 1. a. Typical mixed RC-URM wall structure; b. Schematic sketch of the selected building considered in the current study (all dimensions are in mm)

2. BEHAVIOUR OF SINGLE WALLS AND MIXED RC-URM WALL STRUCTURES

2.1. Behaviour of single URM and RC wall structures

When the coupling of the URM and RC wall is neglected and the two walls are single independent walls, their seismic behaviour differs significantly from their behaviour in a coupled system. Therefore they are considered as uncoupled and they behave as cantilever walls with applied horizontal forces at the height of the storeys. For uncoupled URM walls, the shear deformations govern the behaviour while for a slender uncoupled RC wall, like the one shown in Fig. 1b, the flexural deformations are prevalent. This leads to different inter-storey drift profiles for the two walls at different floor levels. For example, with a triangular load pattern, uncoupled URM walls have higher inter-storey drifts at lower levels while slender uncoupled RC walls have higher inter-storey drifts at upper levels. A schematic representation of crack pattern, deformed shape and inter-storey drift of single RC walls and URM walls are shown in Fig. 2a and 2b, respectively.

2.2. Behaviour of mixed RC-URM wall structures: effect of coupling

In mixed RC-URM wall structures, the walls are connected at each floor by RC beams, which represent the effective width of the RC slabs. The presence of the RC beams changes the behaviour of the uncoupled RC and URM walls. Firstly, due to the presence of the RC beams, the axial force applied on the two walls is not constant but varies during the pushover analysis because the shear force in the RC beams is transferred to the walls as axial force. Secondly, the RC beams impose the same horizontal displacement at each floor on both walls (Fig. 2c). Hence, the inter-storey drift profile of the mixed structure differs from the inter-storey drift profiles of the uncoupled walls, i.e. at the first storey the RC wall enforces to the URM wall smaller inter-storey drift and at the second storey higher inter-storey drift. Furthermore, as the RC beams have to maintain the same horizontal displacement at a floor level, they are subjected to additional axial forces. Finally, cracks and deformations in the RC and URM walls are not concentrated at the first storey, but are distributed along the full height of the building.

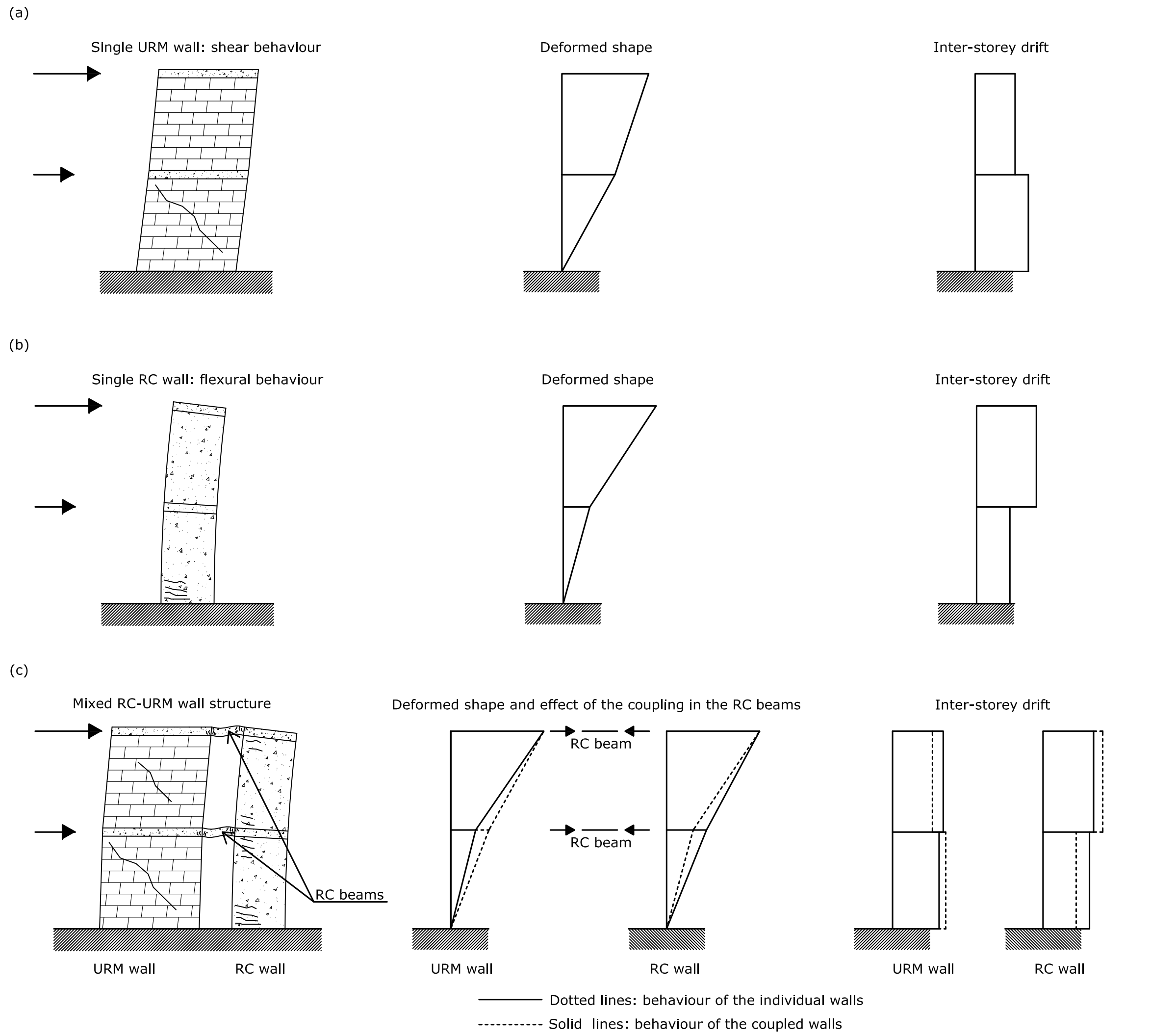


Figure 2. a. Crack pattern, deformed shape and inter-storey drift for single (uncoupled) URM wall structures; b. Crack pattern, deformed shape and inter-storey drift for single (uncoupled) RC slender wall structures; c. Crack pattern, deformed shape and inter-storey drift for mixed RC-URM wall structures coupled by RC beams

3. NUMERICAL MODELLING OF MIXED RC-URM WALL STRUCTURES

For the numerical modelling of mixed structures, two approaches were considered: a simplified micro-modelling/shell element approach, using the software ATENA by Cervenka *et al*. (2010) and a macro-element modelling approach, by means of the software TREMURI by Lagomarsino *et al*. (2009). The example structure shown in Fig. 1b is analysed using these two different approaches.

3.1. Simplified micro-modelling/shell element approach

The simplified micro-modelling/shell element (SE) approach represents the concrete members by means of shell elements with a concrete model. The longitudinal reinforcement is modelled by means of truss elements with a steel model; the shear reinforcement is represented by means of shell elements with a steel model. The URM members are modelled using a micro-modelling approach (Lourenço, 1996). The main characteristics of the SE approach adopted in the current study are listed below:

- The concrete model is capable to capture the inelasticity;
- The steel model is represented by means of a bi-linear with hardening stress strain law;
- Bricks are represented by means of isotropic plane stress elements with elastic properties;

- Mortar joints are represented by interface elements with a Mohr-Coulomb law comprising tension cut off, cohesion softening and tension softening.

The results from the SE approach are considered to be more reliable in comparison to the macro-element modelling approach as the SE approach represents the structure in greater detail using as input parameters material properties that can be obtained from standard material tests. Therefore the SE approach results are used as a reference for the comparison of the modelling approaches. For the selected structure, one model with the simplified micro-modelling/shell element approach was studied and in the following it is named SE model.

3.2. Macro-element modelling approach

The analysis of the selected building using the macro-element modelling approach (ME) is carried out using the software TREMURI by Lagomarsino *et al*. (2009), a program for the simulation of the global seismic response of URM wall structures. In this case, for each single wall a relation between average masonry stress and average masonry strains is established. The so-called "macro-element" (Gambarotta *et al*., 1996.) was adopted for the simulation of cyclic behaviour of masonry elements. Recently, Cattari *et al*. (2006) introduced several non-linear RC elements into the software TREMURI, which allow the analyses of mixed RC-URM structures.

The main characteristics of the ME approaches adopted in the current study are listed below:

- The behaviour of the RC members is described by means of an elasto-plastic law with plasticity concentrated at the elements ends;
- Each single masonry wall is modelled as a homogeneous continuum without distinction between individual bricks and mortar joints;
- To study the overall behaviour of the structure an equivalent frame approach is adopted.

The equivalent frame approach allows the user to define the deformable part of the RC beam by providing rigid offsets. Figure 3 represents various models for the selected structure assuming different offsets to be applied to the RC beams. In all the macro-element models analysed in the current study, the rigid offset is defined in order to have the RC beams deformable between the edges of the walls (configuration as shown in Fig. 3a). The force-deformation characteristics for RC elements in the ME approach are defined by an elasto-plastic law. The stiffness of the RC elements was reduced to account for the effect of cracking by reducing the *modulus of elasticity* (E) of the concrete (Fig. 3c). Similarly, the stiffness of URM walls was also reduced by reducing the *modulus of elasticity* of the masonry. In order to study the effect of the assumed stiffness on the force-deformation characteristics, models combining different assumptions concerning the effect of cracking on masonry and concrete are analysed. The models are summarised in Table 3.1.

Table 3.1. Models combining different assumptions concerning the effect of cracking on the stiffness of RC walls, RC beams and URM walls; *modulus of elasticity E* adopted in the ME models

ME Models	*Modulus of elasticity* of RC walls	*Modulus of elasticity* of RC beams	*Modulus of elasticity* of URM walls
M1	E_{uncr}	E_{uncr}	E_{uncr}
M2	E_{eff} (Equation 3.2)	E_{eff} (Equation 3.2)	0.5 E_{uncr}
M3	E_{uncr}	E_{eff} (Equation 3.2)	E_{uncr}

The modulus of elasticity of the uncracked members E_{uncr} is equal to 7 GPa for URM elements and 36.2 GPa for RC members. Furthermore, for RC members, the effective stiffness E_{eff} is calculated according to Priestley *et al*. (2007) as:

$$E_{eff} = 0.5 \frac{M_N}{I\phi_y} \tag{3.1}$$

where M_N is the nominal moment; I the moment of inertia of the wall section and ϕ_y the nominal yield curvature. The nominal moment M_N is defined as the smaller of the moments corresponding to a compression strain in the extreme concrete fibre of 0.004 and a reinforcement tensile strain of 0.015. The nominal yield curvature ϕ_y is calculated as:

$$\phi_y = 2\frac{\varepsilon_y}{l_w} \tag{3.2}$$

where ε_y is the yield strain of the reinforcements and l_w the wall length.

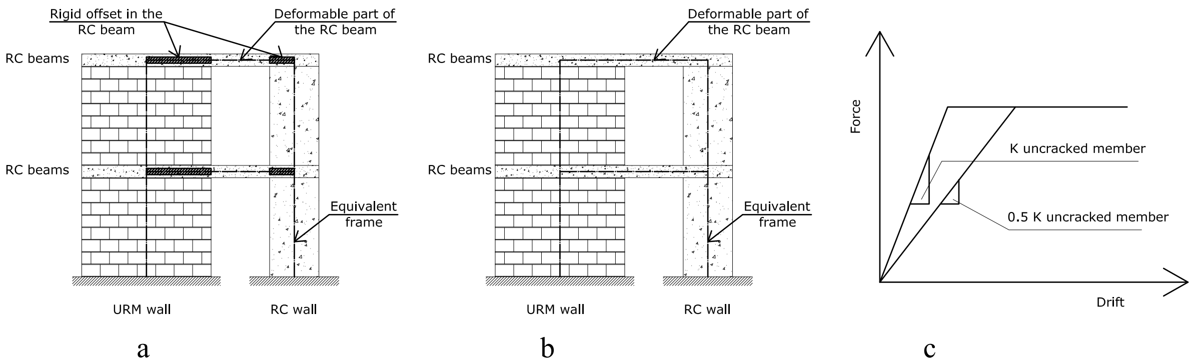


Figure 3. a. and b.: ME approach models for the selected structure with different assumptions concerning the rigid offsets to be defined for the equivalent frame model; c.: effect, on the force-deformation characteristics for a simple cantilever RC wall in the ME approach, of the reduction of the *E* modulus to account for the cracking

4. INFLUENCE OF STIFFNESS ASSUMPTIONS AND MODELLING APPROACHES ON THE DISTRIBUTION OF THE SHEAR AND AXIAL FORCES BETWEEN THE TWO WALLS

4.1. Influence of the modulus of elasticity of the RC and URM elements on the distribution of the shear and axial forces between the two walls

In this paragraph, the influence of member stiffness on the distribution of the base shear and the axial force between the two walls is evaluated. For this purpose, different analyses using the ME approach with various member stiffnesses were carried out. The analysed models correspond to the so-called SE, M1 and M2 (Table 3.1). As explained in Section 3.1, the results obtained from the SE approach are used as reference. A comparison of the results in terms of distribution of the base shear and the axial force between the two walls is shown in Fig. 4.

At first, it can be seen that in M1 a reduction of base shear in the walls is noticed at a drift of around 0.35%, due to the shear failure of the URM wall at the second floor. The reason is because the RC wall governs the deformation pattern as the stiffness of the RC wall is around five times higher than that of the URM wall. The RC wall enforces onto the URM wall higher inter-storey drifts at the second floor than the first. Thus, the second floor reaches the ultimate inter-storey drift δ_u earlier than the first floor and the second storey URM wall fails.

Furthermore, the distribution of the base shear between the two walls is strongly influenced by the assumption of the stiffness. For instance, in model M2 the effective stiffness E_{eff} is used for the RC wall. Indeed the calculated distribution of the base shear from this model corresponds fairly well to the distribution which was obtained with the SE approach. Therefore the simulation with the effective stiffness is assumed to be more realistic. On the other hand, for the model M1, the shear force absorbed by the RC wall is overestimated.

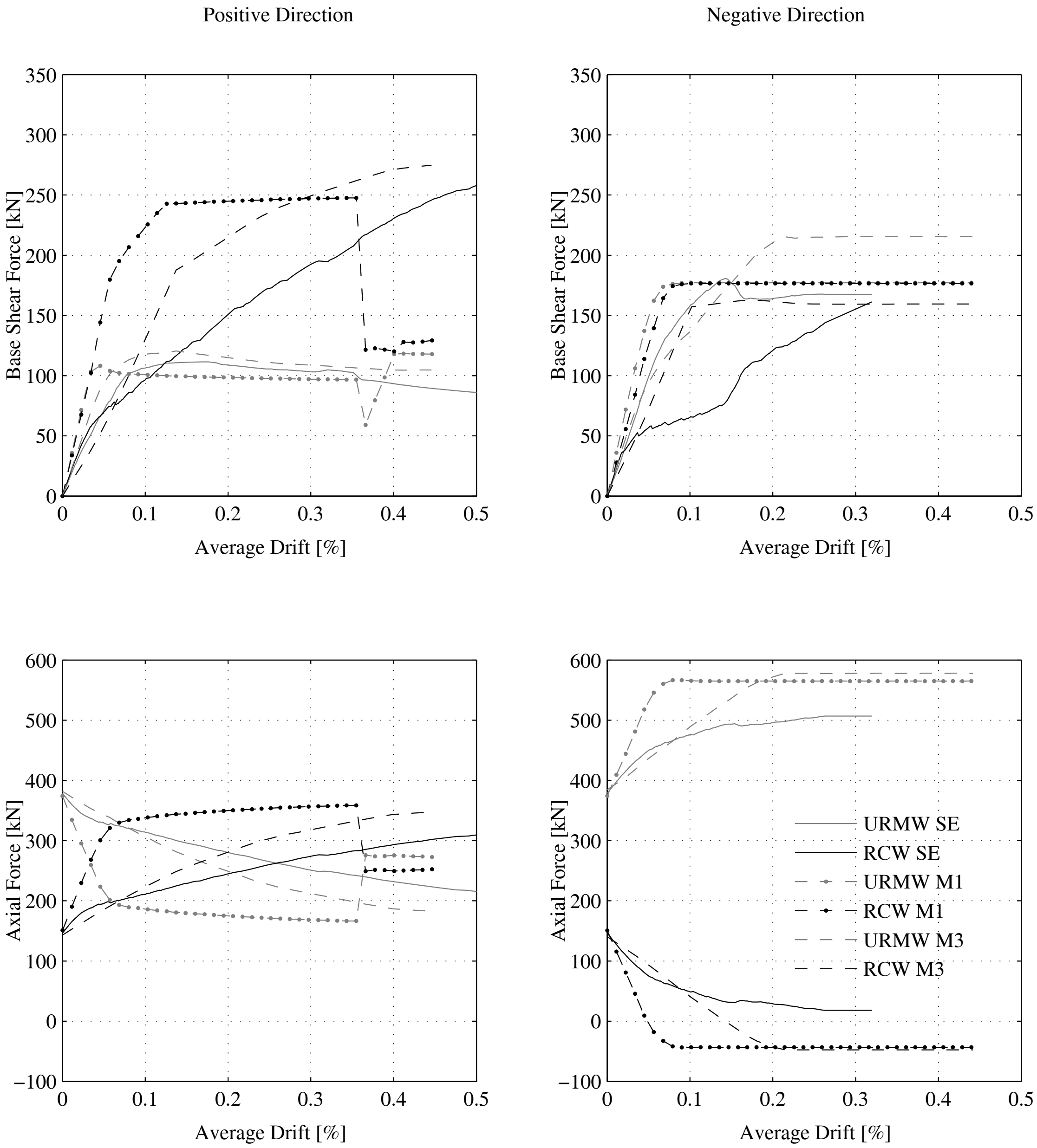


Figure 4. Pushover analyses for the selected structure: distribution of the base shear and of the axial force according to different mechanical assumptions and modelling approaches

4.2. Influence of the *modulus of elasticity* of the RC beams on the distribution of the shear and axial forces between the two walls

In this paragraph, the influence of the stiffness of the RC beams on the distribution of the base shear and the axial force between the two walls is evaluated. For this purpose, different analyses using the ME approach with various member stiffnesses for the RC beams were carried out. The models that have been analysed are SE, M1 and M3 (Table 3.1). A comparison of the results in terms of distribution of the base shear and the axial force between the two walls is shown in Fig. 6.

The influence of the stiffness of the RC beams can be evaluated by means of the coupling effect. The coupling effect can be represented by the (*i*) rate of the axial force transferred between the two walls as a function of the applied inter-storey drift and the (*ii*) maximum change in axial force which is a function of the flexural capacity of the RC beams and the shear span if the beams are developing a flexural mechanism (Fig. 5). The rate of the axial force increases with increasing the stiffness of the

RC beams; the maximum change in axial force instead increases with increasing the flexural capacity and decreasing the shear span of the RC beams. In this paragraph, only the rate of the axial force transferred from one wall to the other is considered, since only the stiffness and not the capacity of the RC beams was varied in the ME models.

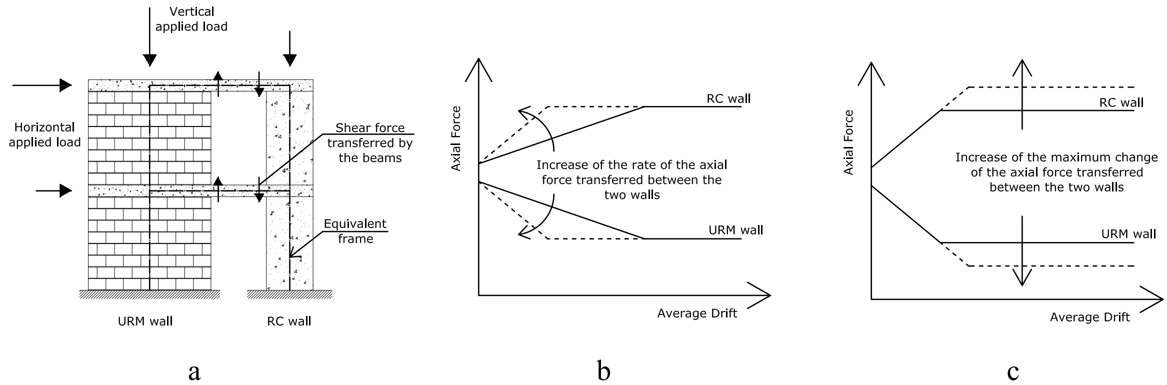


Figure 5. a: Representation of the coupling effect through the variation of the axial force transferred between the two walls by means of the RC beams. b: Increase of the stiffness of the RC beams produces an increase of the rate of the axial force transferred as a function of the applied inter-storey drift; c: Increase of the flexural capacity and decrease of the shear span of the RC beams produce an increase of the maximum change of the axial force transferred between the two walls

Firstly, from the observation of Fig. 6, the coupling effect is overestimated in model M1 if compared to the SE model. Instead, in M3 the variation of the axial force matches fairly well the SE results. This suggests that, in a macro-element modelling approach, the use of the effective stiffness for the RC beams is correct.

Furthermore, in the SE model the exchange of axial load between the two walls is smaller if compared to the ME models. This because in the SE model the RC beams have some curvature penetration into the masonry wall. As a consequence, the free span of the beams increases and the shear force transmitted, which corresponds to a variation of axial force applied to the walls, decreases. Figure 7 shows the deformed shapes of the SE model and the points of maximum curvature in the RC beams.

4.3. Influence of the modelling approach on the force-deformation characteristics on the distribution of the shear and axial forces between the two walls

In this paragraph, the influence of the modelling approach on the distribution of the base shear and the axial force between the two walls is evaluated. Two main differences could be indentified:

First, the two approaches predict a different failure mechanism for the URM wall. While a pure shear failure is obtained with the ME approach, the SE approach predicts a mixed shear-rocking failure (Fig. 7). One possible reason of the different failure mechanism could be caused by the coupling effect: in the ME models the coupling tends to be overestimated in comparison to the SE model. The coupling increases the moment gradient in the wall and thus, shear failure is favoured in the ME models.

Furthermore, the ME approach can only account for the global plastification of a single wall, while the SE approach is also able to account for partial cracking of the URM wall, e.g. the failure of one contact interface. This leads to small differences in the response. In addition, since the ME model can only capture the global plastification of a single wall, this approach is not able to capture mixed shear-rocking mechanisms, but only pure shear or rocking failure.

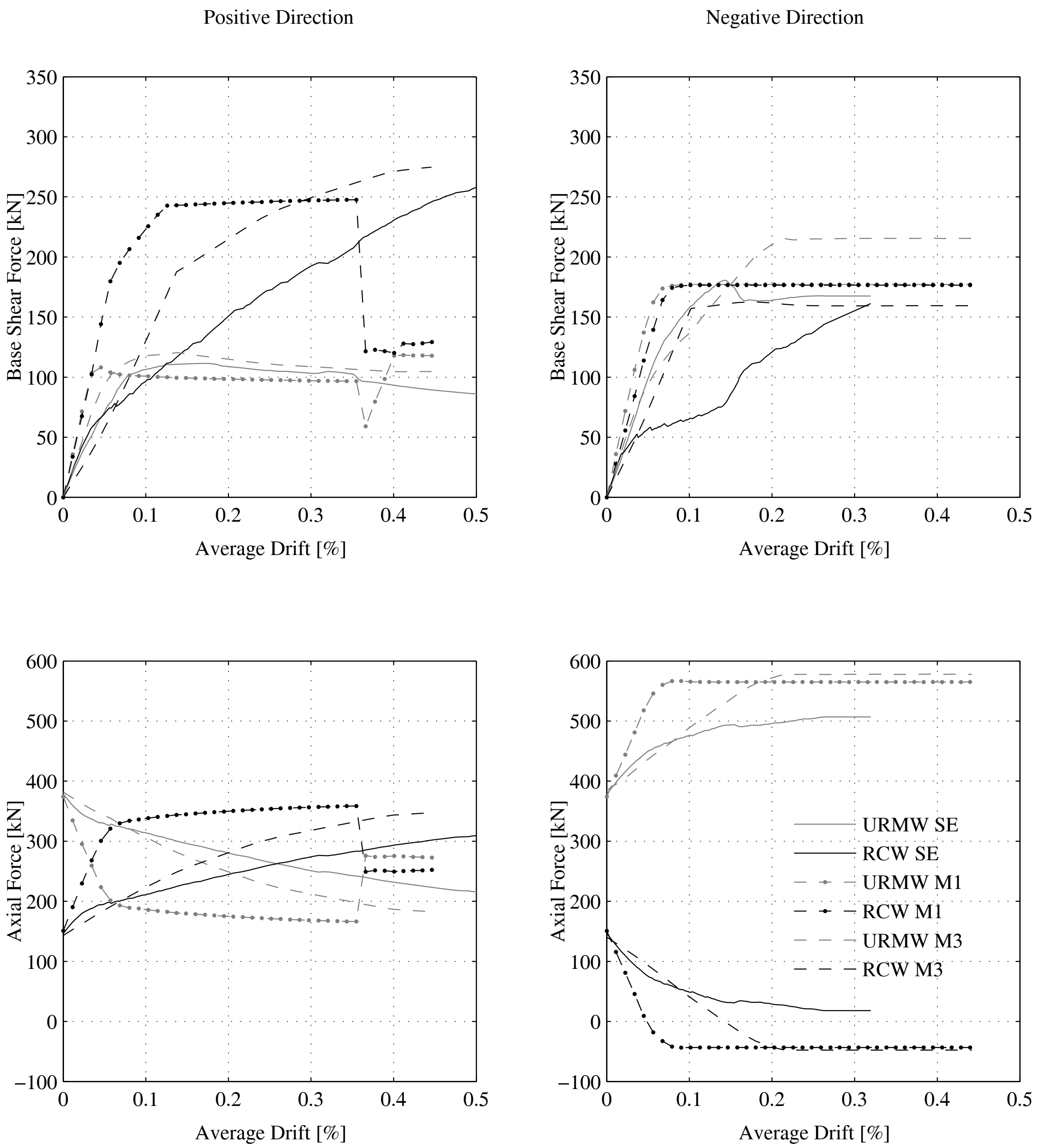


Figure 6. Pushover analyses for the selected structure: distribution of the base shear and of the axial force according to different mechanical assumptions and modelling approaches

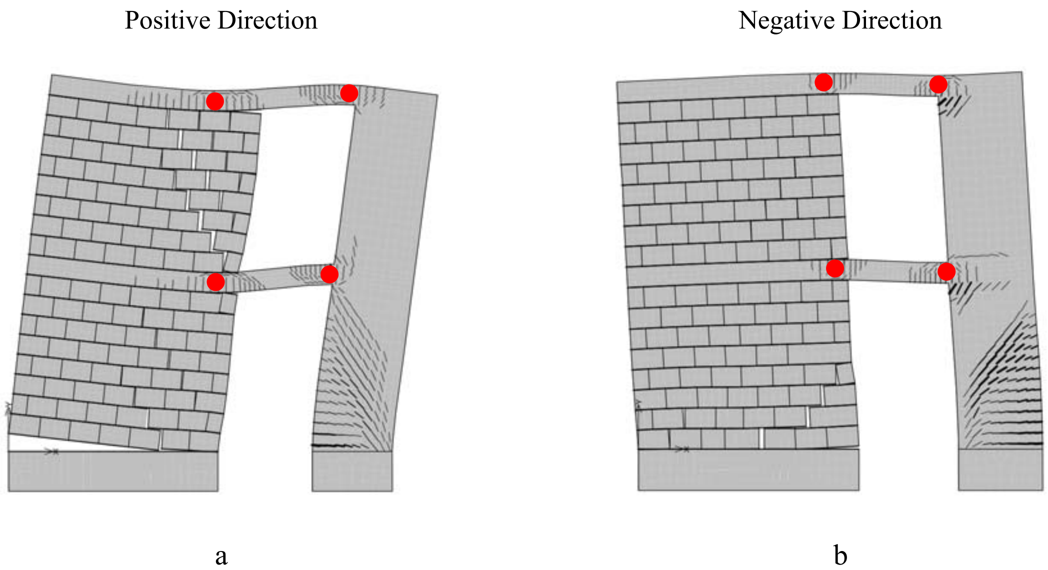


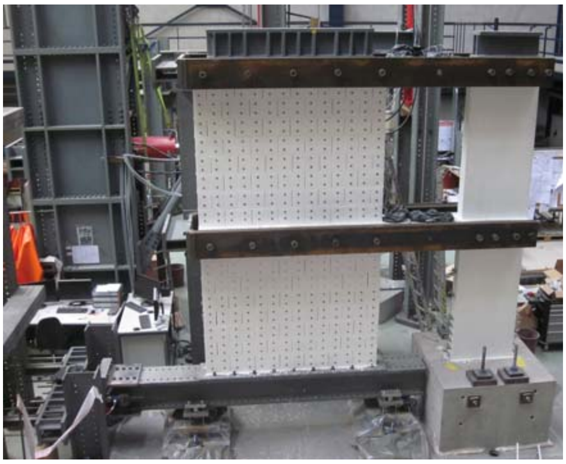
Figure 7. SE models, a. positive direction, b. negative direction; deformed shape, crack pattern at a drift of 0.3% and points of maximum curvature in the RC beams (red points). Magnifying factor: 20.

5. CONCLUSIONS

In spite of the popularity of mixed RC-URM wall structures, they are generally designed using over-simplified approaches for seismic loads and URM walls are often neglected for the seismic resistance. This interpretation is not correct since a strong interaction between the structural elements does exist. In addition, although URM walls are often neglected for the seismic capacity of the structure, they are considered as load bearing walls for gravity loads. Figure 7 represents the deformed shapes and the crack patterns of the selected structure at a drift of 0.3%: also the URM wall is damaged and hence contributes to the seismic resistance of the structure. As the URM wall is damaged it has to be checked whether it is capable to carry the vertical loads.

The paper presents the results of a study to compare the response of mixed RC-URM wall structures considering various analysis approaches and mechanical assumptions for RC and URM elements. A two-dimensional two storey building was considered in the current study and it is composed by a URM wall and a RC wall connected by means of RC beams. Different analyses carried out with a macro-element modelling (ME) approach were compared between each-other and with a micro-modelling/shell element (SE) approach. The distribution of base shear and axial force between the two walls are strongly dependent upon the modelling assumptions and the mechanical properties adopted for the single members of the structure. As the SE model captures the interaction between RC and URM walls in greater detail, it is assumed that the results are closer to reality than those of the rather simple ME models whose results are strongly influenced by assumptions on the effective stiffness of RC and URM members and the effective span of the RC beams representing the effective width of the RC slab. However, SE models are inappropriate for design purposes as they are too computational expensive. For this reason, we aim at deriving modelling guidelines for ME models that lead to a good approximation of the computationally expensive SE models, for example the effective beam length. The analyses presented here have shown that assigning the RC walls the effective stiffness is appropriate concerning the distribution of the base shear between the two walls. In addition, assigning the effective stiffness to the RC beams yielded a good approximation of the rate of axial force transferred from one wall to the other.

This paper is a part of a research programme initiated at the EPFL with the objective to contribute to the understanding of the seismic behaviour of such mixed RC-URM wall structures: both numerical and experimental investigations will be carried out. In particular, the same selected wall system is going to be tested at the EPFL laboratory within an experimental campaign. One objective of the test is to evaluate and assess the different modelling approaches. A particular test set up will allow the measurements of the reaction forces (axial force, bending moment, shear force) at the base of the URM wall, as well as global deformations (displacements of each storey). From the applied horizontal and vertical loads the reactions at the base of the RC wall will be deducted. Figure 8a shows an overview of the test unit, while Fig. 8b focuses on the set up designed to measure the reaction forces at the base of the URM wall.



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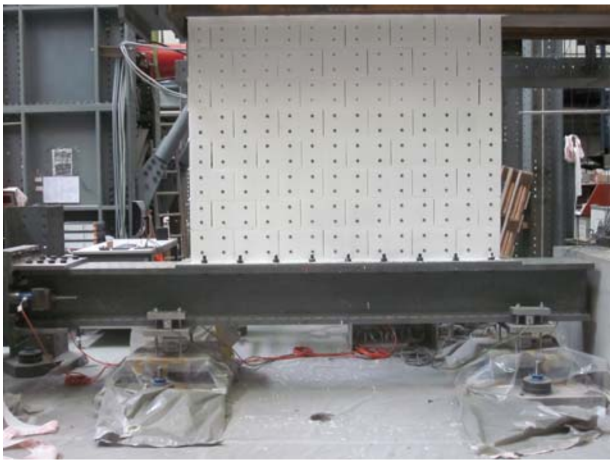

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Figure 8. a. Overview of the test unit; b. Particular of the set up designed to measure the reaction forces at the base of the URM wall

ACKNOWLEDGEMENTS
The authors wish to thank Sujith Mangalathu for his comments on the manuscript.

REFERENCES

Cattari, S. and Lagomarsino, S. (2006). Non Linear Analysis of Mixed Masonry and Reinforced Concrete Buildings. *1st ECEES.*

Cervenka, V., Jendele, L. and Cervenka, J. (2010). Atena- Computer Program for Nonlinear Finite Element Analysis of Reinforced Concrete Structures. *Theory and User Manual*, Prague, Czech Republic.

Gambarotta, L. and Lagomarsino, S. (1996). On the Dynamic Response of Masonry Panels. *Proc. of the National Conference "La Meccanica delle Murature tra Teoria e Progetto."*

Lagomarsino, S., Penna, A., Galasco, A. and Catatri, S. (2009). Tremuri User Guide, Genova, Italy.

Lourenço, P.B. (1996). Computational Strategies for Masonry Structures, Delf University Press, Delf, The Netherlands

Priestley, M.J.N., Calvi, G.M. and Kowalsky, M.J. (2007). Displacement-Based Seismic Design of Structures, IUSS Press, Pavia, Italy