BOUNDARY CONDITIONS OF SHEAR WALLS IN MULTI-STOREY MASONRY STRUCTURES UNDER HORIZONTAL LOADINGS

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SUMMARY

Under horizontal loads, e.g. due to wind or earthquake actions, the distribution of the lateral forces to the several shear walls in multi-storey masonry structures is calculated usually assuming a linear-elastic behaviour, though this approach is mechanically inaccurate. To study theses effects, numerical investigations have been carried out on a spatial finite-element system. The RC-floor slabs were considered remaining uncracked and the vertical shear walls were described by a nonlinear material law. From the results the changing distribution of the lateral loads to the shear walls and also the stress state in each wall was determined.

INTRODUCTION

In multi-storey structures the distribution of the horizontal loads to the shear walls commonly is calculated under the assumption of linear-elastic behaviour of the structure. As unreinforced masonry shows an explicit nonlinear behaviour under combined loadings this assumption leads especially under high horizontal loadings, to inaccurate results. Under seismic loadings also the stiffness of the structure is important, as the corresponding horizontal load results from the dynamic equilibrium in an interaction of seismic input and dynamic behaviour of the structure. Due to the lack of knowledge numerical investigations have been carried out on spatial Finite-Element-Models of whole structures – for 2-storey terraced-house structures and for the here presented multi-storey apartment-house structures. Due to the numerical effort, the investigations were carried out using a smeared modelling of the material properties of unreinforced masonry. Thereby local effects, like the influence of

the unit size / the format or the perforation pattern couldn't be determined. For the calculations, a non-linear behaviour of the masonry has been taken into account.

INVESTIGATED STRUCTURES

Plans

The following two plans – named as *Apartment-House Type 1* (*AH1*) and *Type 2* (*AH2*) – were assumed to be representative for typical multi-storey residential buildings. In a second step also the effect of the increasing length of shear walls (*AH1*) and modification of the plan (*AH2*) was covered. The effect of lintels and the masonry below window openings was neglected.

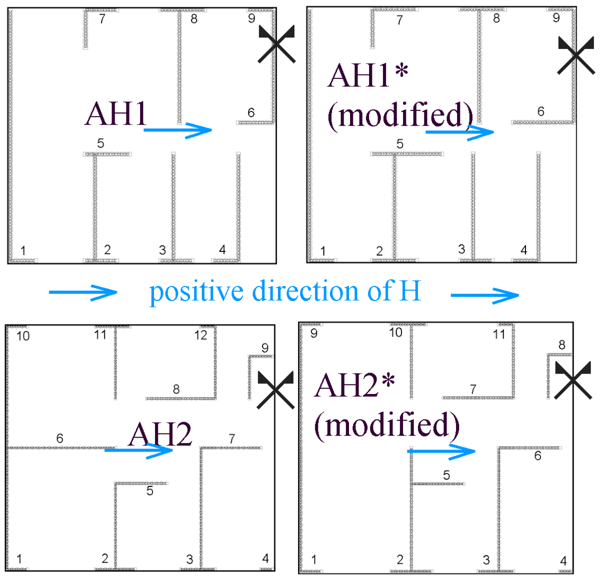


Figure 1. Plan view of the investigated structures (half structure due to symmetric effects).

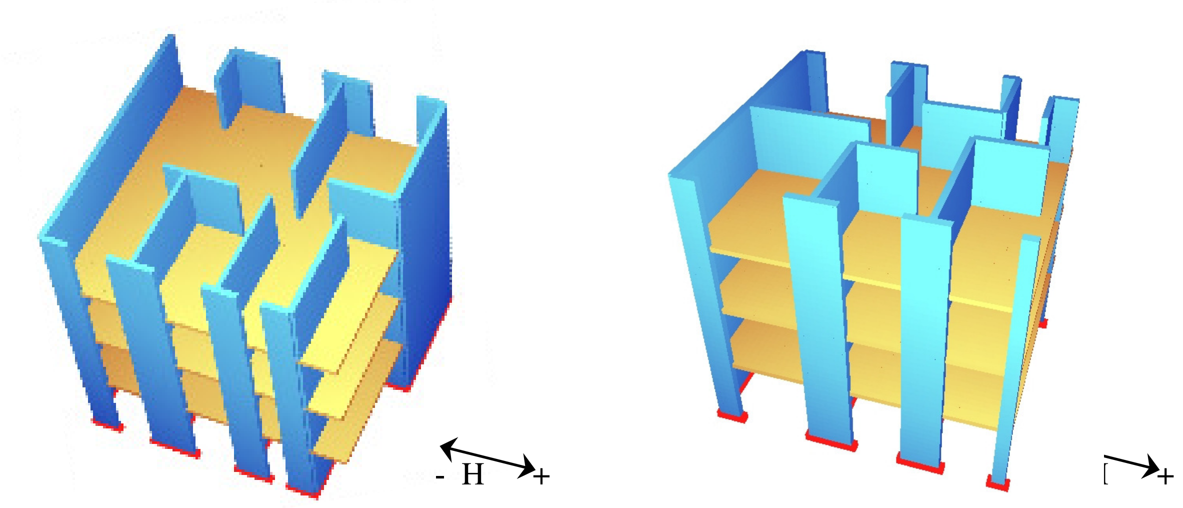


Figure 2. Isometric view of the investigated structures (half structure due to symmetric effects) after the modifications, left side: *Apartment House Type 1**; right side: *Apartment House Type 2**

Geometric properties

The number of storeys was varied between 3 and 4 to investigate and quantify this effect. To reduce the numerical effort, the system was reduced due to symmetric effects to the half structure. The staircase is located in the plans down right. For the spatial model the stair-plate has been placed horizontal extending the regular slab. The structure was investigated under horizontal forces acting in the "weak" direction. Investigations with impact in the strong direction were left out, as not being relevant.

It was simply assumed that the opening for the doors and windows take the full storey height, i.e. no load bearing parapet or lintel exist. This simplification was necessary to reduce the effort of the numerical spatial investigations using the finite-element-method.

The thickness of the walls was taken to 17.5, 24 resp. 30 cm with the same mechanical parameters given in section 4.2 (representing vertically perforated clay-bricks or calcium-silicate units with cement-lime-mortar and a compression strength of about 8.5 N/mm² and a E-modulus of 8500 N/mm²). The storey height was taken constantly to 2.75 m with a thickness of the C20/25-concrete slabs of 20cm.

Table 1. Geometric parameters of the investigated structures.

AH1: Wall No.:	1	2	3	4	5	6	7	8	9			
Length l [m]	1	1,25	1,25	1	1,75	1,4	1,25	1,75	1			
Thickness d [cm]	24	24	24	24	17.5	24	24	24	24			
AH1*: Wall No.:	1	2	3	4	5	6	7	8	9			
Length l [m]	1	1,75	1,25	1	2.75	2.4	1.75	1.75	1			
Thickness d [cm]	24	24	24	24	17.5	24	24	24	24			
AH 2: Wall No.:	1	2	3	4	5	6	7	8	9	10	11	12
Length l [m]	0.875	1.75	1.5	0.5	2.25	4.75	2.625	3	1	0.875	1.5	0.625
thickness d [cm]	30	30	30	30	24	30	30	30	24	30	30	30
AH 2*: Wall No.:	1	2	3	4	5	6	7	8	9	10	11	
Length l [m]	0.875	1.75	1.5	0.5	2.25	2.625	3	1	0.875	1.5	0.625	
thickness d [cm]	30	30	30	30	24	30	30	30	30	30	24	
*: modified model												

NUMERICAL INVESTIGATIONS AND BOUNDARY CONDITIONS

Numerical Investigations

The numerical investigations have been carried out on a spatial finite-element system using shell elements. The RC-slabs were considered remaining uncracked and the vertical shear walls were described by a nonlinear material properties. The interface between horizontal RC-slabs and the vertical masonry walls was assumed to be fix as tension failure perpendicular to the bed joints is included in the material properties of the masonry walls. The basement was assumed to be very stiff and therefore not deciding for the dynamic behaviour of the structure and for the failure modes. Therefore the basement was neglected. The fixing of the structure was assumed to be stiff without any flexibility. The chosen finite-element-approximation enables to cover shell deformations and also plate deformations. The latter is realized by a splitting of the plate-bending in 2 parallel shell components. Therefore a differentiation in a lower and an upper component resp. side is made

Load and load application

For the calculations vertical and also horizontal loads were considered. The vertical loads were taken to the dead load of the structure and the quasi-permanent value of the live load according Eurocode 8. The vertical loads were simplified applied using a constant plane load in the concrete slabs including also the dead loads of the walls.

The horizontal load was applied by point loads in the slabs in each storey. The position in the horizontal direction was determined in the centre, as no torsional effects were intended. The distribution over the height of the structure was taken to a linear approximation of the first eigenform.

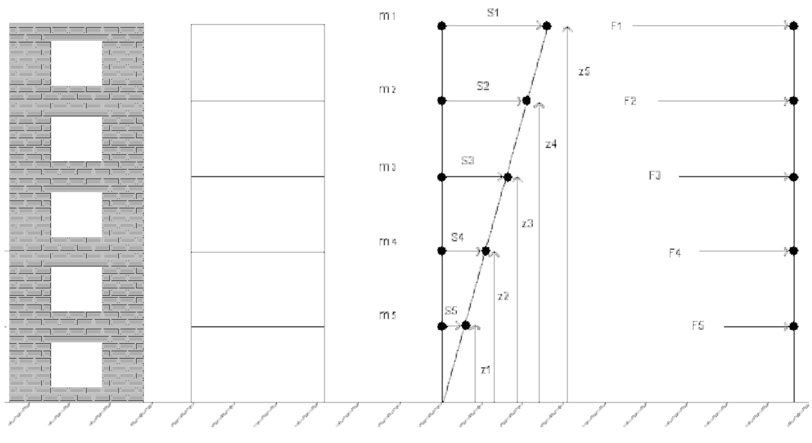


Figure 3. Estimated 1st eigenform of the structure and corresponding distribution of the horizontal force H to the storeys (schematic view on a 5-storey structure).

The direction of the horizontal load was set in the weak direction – in the given plans orientated from right to left and vice versa.

MATERIAL PROPERTIES

Concrete

As explained above the concrete slabs were assumed to remain uncracked and behave linear-elastic. The Young-modulus was taken to 30,000 N/mm². The mass of the concrete was modified to cover the total dead load (concrete slabs and also masonry walls) and the permanently present live load in the load-case earthquake.

Masonry

For the vertical masonry walls under combined vertical and horizontal, i.e. combined normal-, bending- and shear-stress simple non-linearities had to be considered in its material law.

In the preliminary stage several given in literature material laws were reviewed and tried to integrate in existing FE-programmes. As a result it was found, that due to the numerical effort (spatial investigations of whole apartment house structures) and suitability of the FE-programmes the only possible failure criterion covered in a smeared material law was tension failure. As the principal (tense) strain and stress under combined stress deviate from the orientation of the joints in the masonry, the assumption of a general tension failure contains in this regard a specific error. Nevertheless the description of the tension failure perpendicular to the bed joint using an isotropic failure criterion was assumed to be sufficient, proven by calculations on a cantilever wall. Even assuming an evanescently tension strength perpendicular to the bed joint in the calculations, a strength greater than zero has to be supplied for numerical reasons. Also in the regions of singularities (e.g. corners), of load application and of the coupling of horizontal and vertical shell-elements singular tensions peaks appear due to numerical reasons. Applying the finite-element approximation, with these effects without any tension strength a brittle failure will be indicated. Therefore a small isotropic tension-strength of 0.18 resp. 0.3 MN/m² was chosen.

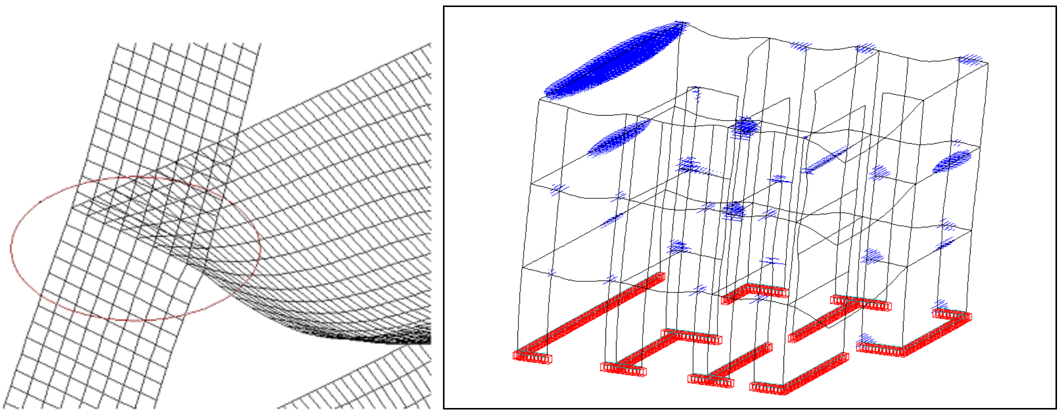
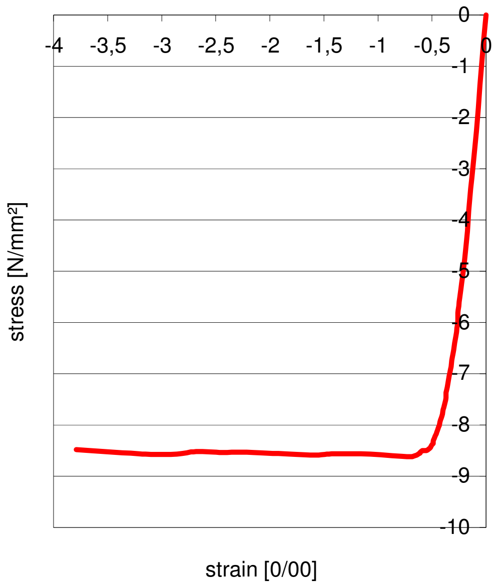


Figure 4. Left side: Coupling of slabs and walls (deformed shape), right side: Regions of plastic deformations (upper side of the 2-layer shell-system) in the 3-storey Apartment-House 1-structure under H_{total}=133kN.

Under compression these kinds of singularity effects also appear, but no brittle failure occurs, as stress redistribution is possible. On the other hand, under high uniaxial compression stresses a plasticity of masonry is observed in experimental tests. Thus, for masonry under

compression an ideal plastic behaviour was chosen when reaching the compression strength. This effect could be described as ductile. In the following the strain-stress-relationship under compression (compression strength 8.5 N/mm²) and under tension (tension strength 0.18 N/mm²) is shown. The behaviour under tension also includes the fracture energy and the used element approximation.

a) b)



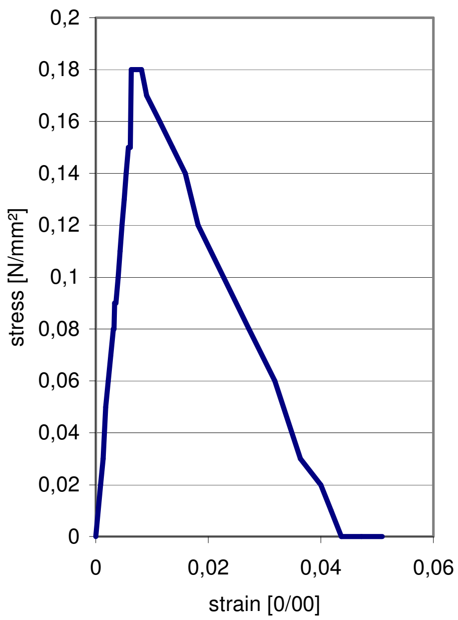


Figure 5. Strain-stress-relationship of the used material law under a) uniaxial compression (compression strength 8.5 N/mm²) and under b) uniaxial tension (tension strength 0.18 N/mm²) of a single wall element

The calculations using the finite-element method were performed with element dimensions of about 0.2m x 0.2m.

RESULTS

General

The results of the calculations were analysed to determine the distribution of the horizontal loads to the several shear walls. The values are plotted in relation to the load level, i.e. the total horizontal load H. This load was applied with a positive and also a negative sign.

As under seismic loadings and the distribution of the horizontal seismic forces along the height of the structure the relevant area is generally the first storey, all investigations focus on three sections in the 1st storey: at the top of the wall (about 0.2m under the upper slab), in the middle of the wall and at the base of the wall (about 0.2m above the fixings).

In the following sections only the distribution in the middle of the walls in the 1st storey of 4-storey-structures are shown.

Apartment House 1

The distribution of the horizontal load is shown in the following figure.

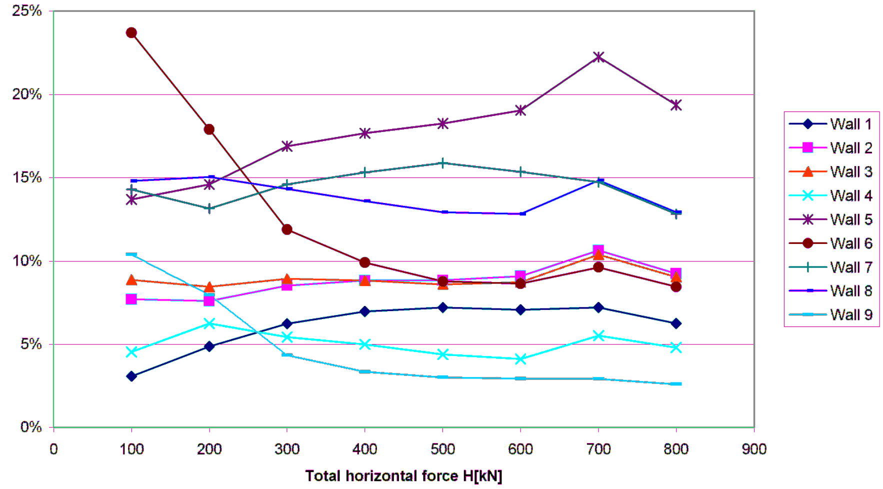


Figure 6. Distribution of the horizontal load H to the shear walls (positive direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, Apartment-House 1)

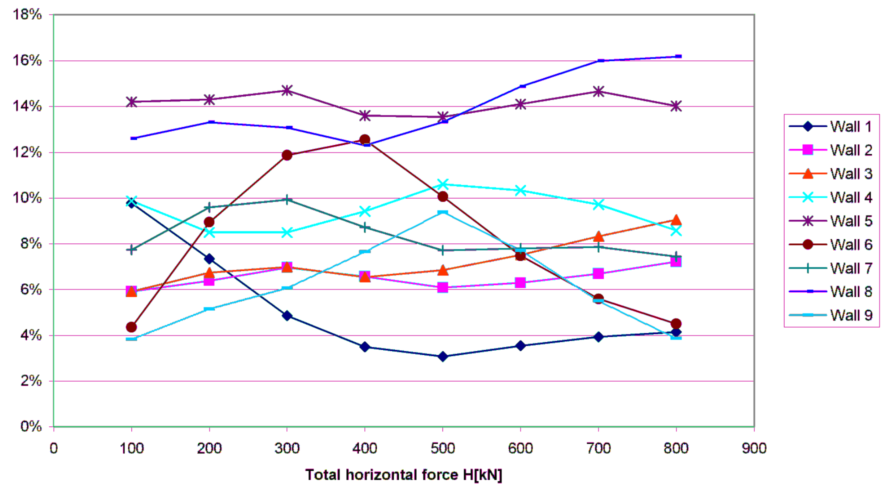


Figure 7. Distribution of the horizontal load H to the shear walls (negative direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, Apartment-House 1)

Comparing the distribution of the horizontal forces in the middle of the wall with different orientation of the external horizontal force H a significant difference appears. This effect could be explained with the configuration of the transverse walls in function of a flange and the orientation referring to orientation of the external horizontal force. This effect is found especially at wall no. 5 (centric flange => almost no difference between the two orientations of H) and 6 (with one-side flange => difference between the two orientations of H).

Generally it is obvious, that long walls – with a high stiffness assuming an uncracked cross section – are sensitive to the opening of the cross sections due to in-plane bending moments and the corresponding reduction of the compressed cross section.

Apartment House 1*

The distribution of the horizontal load is given below.

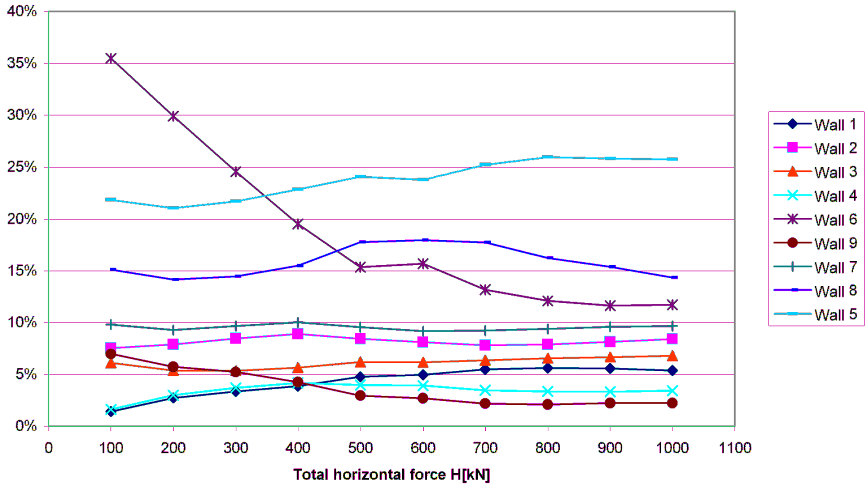


Figure 8. Distribution of the horizontal load H to the shear walls (positive direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, modified Apartment-House 1, AH1*)

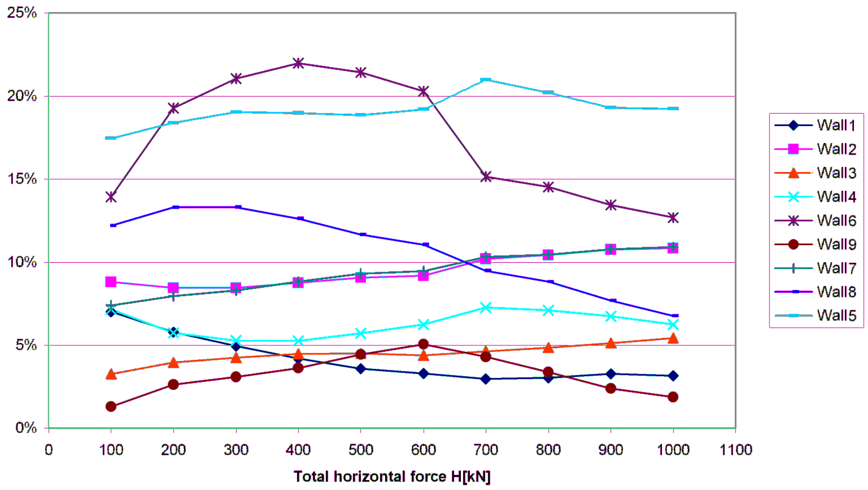


Figure 9. Distribution of the horizontal load H to the shear walls (negative direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, modified Apartment-House 1, AH1*)

With the modification of the plan view – increased lengths of the walls 2, 5, 6 and 7 – a different distribution of the shear loads is found. Especially the shear loads on wall 5 and also on wall 7 increases significantly where the shear-load on wall 6 decreases (at positive orientation of H immediately and at negative direction of H after a phase of increase).

Apartment House 2 and Apartment House 2*

The distribution of the horizontal load is given below.

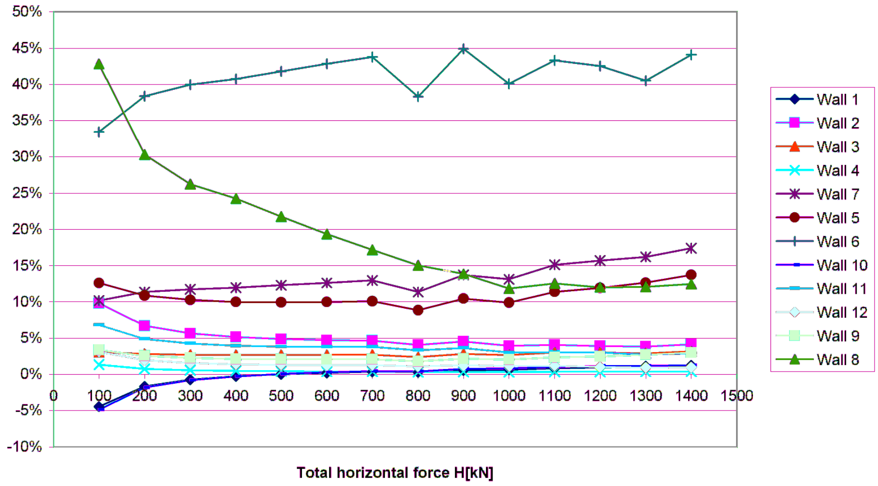


Figure 10. Distribution of the horizontal load H to the shear walls (positive direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, Apartment-House 2)

The horizontal load on wall 8 is reduced (positive direction of H) significantly with increased load level where the horizontal load of wall 6 remains almost constantly (about 40%).

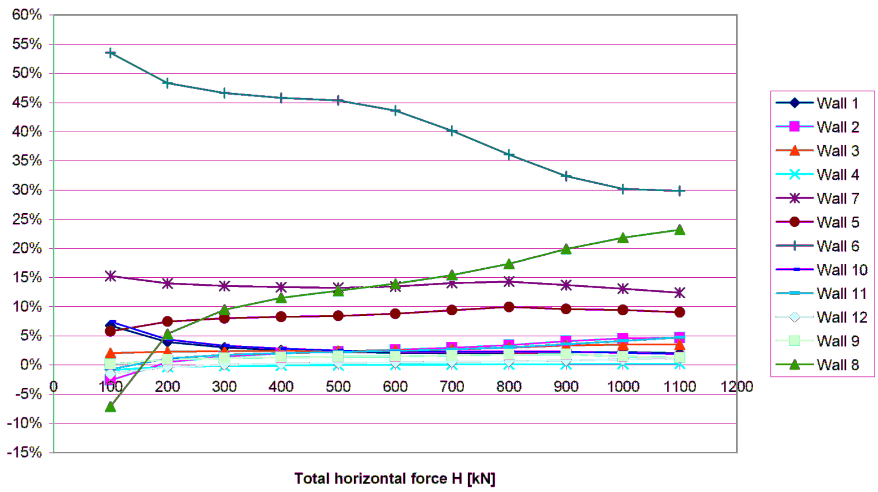


Figure 11. Distribution of the horizontal load H to the shear walls (negative direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, Apartment-House 2)

With the negative orientation of H the load on wall no. 6 starts at 55% and reduces with the increasing load level to 30%, where the load on wall 8 increases to 23%.

The distribution of the horizontal load in the structure Apartment House 2* (modified Apartment House 2) is given below.

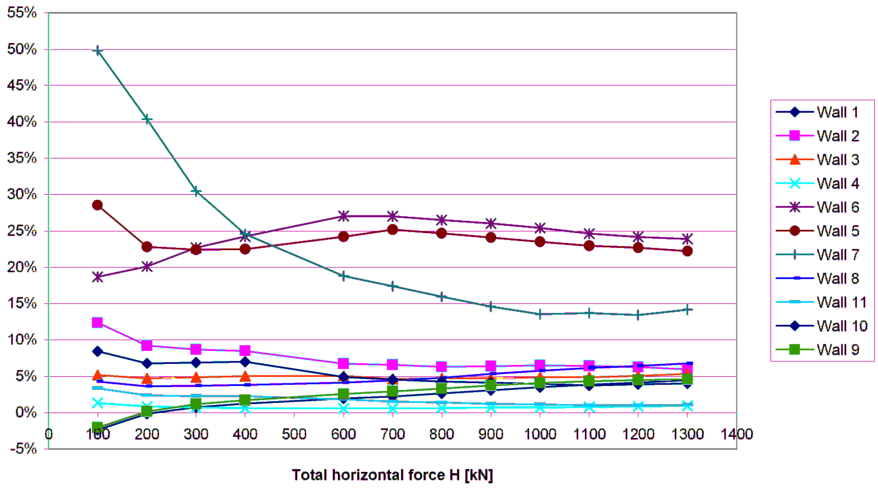


Figure 12. Distribution of the horizontal load H to the shear walls (positive direction of the horizontal load H, distribution in the middle of the wall in the 1st storey, modified Apartment-House 2, AH2*)

With the removed wall no. 6 of the AH2-structure here the main horizontal load is carried by the wall no. 7 (corresponding to the no. 8 in the AH2-structure). The reduction of the load of this wall with increasing load level is comparable with the behaviour in the structure AH2 (=wall no. 8). In opposition to the AH2-structure the 2 other "long" walls no. 5 and 6 (AH2*) take about 2 x 25% of the total horizontal load (in AH2: walls no. 5 and no. 7: 2 x 13%).

Summary

The distribution of the shear loads changes significantly with rising load level. During the calculations – especially on the Apartment House 2-structure – it was found, that due to plate deformations of the transverse walls in the mentioned section secondary horizontal shear stresses resp. corresponding forces appeared. For the equilibrium of state in the mentioned walls orientated in longitudinal direction counteracting forces resulted. With rising external horizontal force H this effect was reduced. Further due to plate shear loadings approximately 10% of the total horizontal force was carried by the transverse walls. This has to be considered when comparing the impact load H and the sum of the shear forces in the mentioned walls (important at higher load levels).

The determination of the position of the resulting normal force N in each wall-section – latter was described by the eccentricity e – is given in detail in [2]. Regarding the normal stresses a significant difference between the investigated sections, i.e. cap, middle and base of the wall, was recognized. This effect enhanced with rising load levels, as the non-linear-effects, especially opening cross-sections due to exceeding tension strength, dominate.

CONCLUSION

The distribution of the horizontal loads to the shear walls was investigated using a spatial finite-element model. The nonlinear behaviour of unreinforced masonry was covered by a smeared material law. The calculations were done on a 3- and 4-storey structure and 4 types of plans. The direction of the horizontal load was taken in the weak direction and applied in positive and also in negative direction with different load levels.

It was found, that the distribution of the shear load to the walls changes significantly with the load level. Also a difference between the positive and negative orientation of the external load was found.

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