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PSEUDO-DYNAMIC TESTS ON A FULL SCALE MASONRY BUILDING

U. Meyer
Technische Geschäftsführung, Arbeitsgemeinschaft Mauerziegel e.V.,
Schaumburg-Lippe-Str. 4, 53113 Bonn, Germany, meyer@ziegel.de

ABSTRACT

A full scale unreinforced masonry terraced house has been subjected to pseudo-dynamic tests to verify the resistance against earthquake loads in areas of low and moderate seismicity. The tests were part of ESECMaSE, a four year research project on European level, incorporating a total of 26 partners from research and industry in seven European countries.
Preliminary tests on shear walls were carried out using a new test set-up developed within the project. The structure resisted the design earthquake for the moderate seismicity regions in Central Europe without significant cracking. The resistance of the building was significantly higher than it could be expected by the results of the preliminary tests on shear walls. This seems to be due to a redistribution of loads and the effect of combined cross sections. The commonly used cantilever design approach for unreinforced masonry shear walls does not seem to be appropriate.

KEYWORDS: clay unit masonry, earthquake resistance, pseudo-dynamic testing, shear resistance.

INTRODUCTION

Within the scope of the European joint research project ESECMaSE comprehensive investigations were carried out on the shear load bearing capacity and earthquake resistance of masonry.

A large-scale pseudo-dynamic test on a terraced house with a typical Central European ground plan was scheduled as the final experiment in the project. Results of preceding investigations within the ESECMaSE project have already been presented at IBMaC in 2008 [1 to 8]. The main purpose of this large-scale test was the examination of the transferability of the findings and conclusions of the previous investigations. In particular it served to check the developed design models on a structure subjected to loading under near-practice conditions.

Figure 1 shows the ground plan and elevation of the specimens (terraced house halves). One specimen was built with clay unit masonry, the other one with calcium silicate masonry. This paper focuses on the investigations on the clay unit structure.

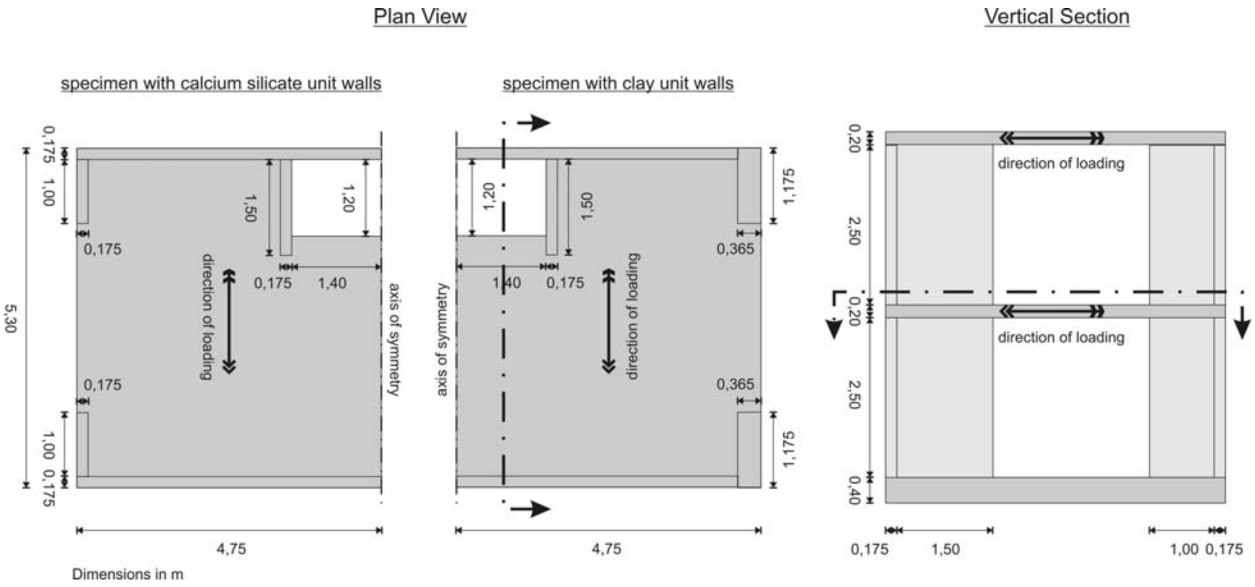

Figure 1: Ground plan and elevation of the two storey specimens tested in Ispra [10,13]

PRELIMINARY STATIC-CYCLIC TESTS AT THE UNIVERSITY OF PAVIA (ITALY)

For the specimen in clay unit construction, two tests were carried out at the University of Pavia [9] with the applied normal forces foreseen in the large-scale test in Ispra. The set-up for the static-cyclic tests at the University of Pavia is shown in Figure 2. The tests were carried out with the boundary condition “Point of zero moment in the mid height of the wall”, which according to the numerical preliminary investigations in the project represents the most realistic boundary condition in masonry buildings with reinforced concrete floors.

Figure 2: Test set-up for static-cyclic in-plane shear tests in Pavia [9]

Figure 3 (left) shows the horizontal force-displacement curves of the test CL 01 with unreinforced infill units according to the German technical approval Z-17.1-537 (figure 4, centre), and Figure 3 (right) those of the test CL 03 with thermal insulating clay units according to the German technical approval Z-17.1-490 (figure 4, left).

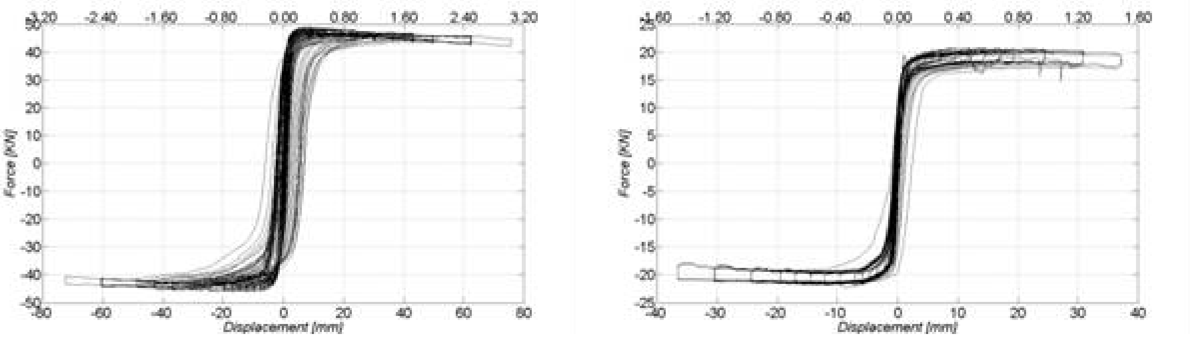

Figure 3: Horizontal force-displacement curves; left: main shear wall CL 01 (normal force 81 kN); right external wall CL 03 (normal force 51 kN)

Due to the low applied loads resulting from the boundary conditions in the terraced house, both specimens were able to absorb large displacements at the wall head up to the end of the test, without a significant reduction of the horizontal load bearing capacity. The test CL 01 (infill units) was stopped without failure of the wall, as the displacement of 70 mm at the wall head corresponded to the maximum piston stroke of the horizontal cylinder of the testing facility. In the test CL 03, with displacements of about 25 mm cracks formed, which followed the vertical and horizontal joints, but which did not lead to a decrease of the horizontal load bearing capacity, because diagonal struts could still develop in the specimen. Magenes concludes among other things from this in [9] that an essential positive element of aseismic construction is a moderate utilization of the compressive load bearing capacity of the shear walls, because with increasing normal force the failure becomes far more brittle.

TEST SET-UP AND CONSTRUCTION OF THE LARGE SCALE PSEUDO-DYNAMIC TEST

The large-scale pseudo-dynamic tests in Ispra were carried out on two terraced house halves with the ground plan and elevation shown in Figure 1. Three types of clay units were used for the specimen in clay unit construction, see Figure 4.

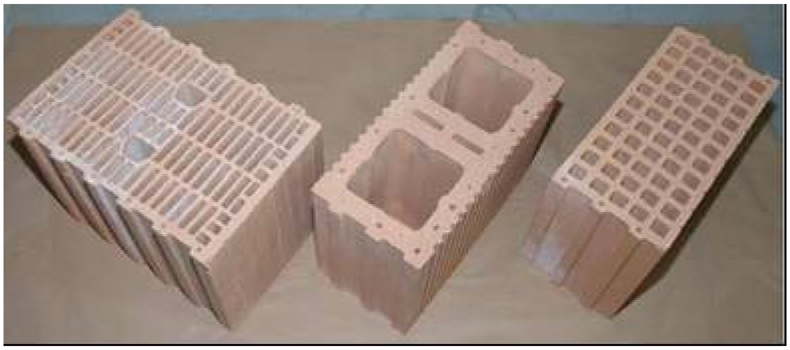

Figure 4: Clay units applied in the tested structure; thermal insulating unit (left), infill unit (centre), optimised unit (right)

For the external walls at the front side of the building, 365 mm thick lightweight vertically perforated precision units according to the German technical approval Z-17.1-490 were used (Figure 4 left). The interior walls (shear walls) were constructed with 175 mm thick infill units according to the German technical approval Z-17.1-537 (figure 4 centre), which were filled with unreinforced concrete (C 20/25). The long partition walls were built of 175 mm thick optimized vertically perforated precision units according to the German technical approval Z-17.1-993, which were also a result of the project (figure 4 right). Table 1 gives some material properties of the units.

Table 1: Dry density, percentage of voids, compressive strength f_b, longitudinal compressive strength f_{bl} and splitting tensile strength $f_{t,sp}$ of the units applied in [13]

Clay unit type	Dry density kg/m³	Voids %	f_b	f_{bl}	$f_{t,sp}$
			N/mm²		
PHLz Z-17.1-490	770	49	13,1	2,7	0,34
PFz 10 Z-17.1-537	750$^{1)}$	46,1	13,6$^{1)}$	Not determined	0,70$^{1)}$
Optimised PHLz 12 Z-17.1-993	850	43	16,9	4,8	0,83

$^{1)}$ without concrete infill

With the exception of the first horizontal joint in each case, for which a general-purpose mortar M5 was used, a thin-layer mortar was used for the clay unit masonry. The connection of the walls to each other was done by flat steel anchors. The clear storey height was 2,5 m.

A 400 mm thick base slab of reinforced concrete served as a foundation, which was anchored immovably to the hall floor (stressing field). The horizontal loads were applied via altogether 4 hydraulic pistons, two of these elements were applied on the floor slabs at opposite sides and braced with each other. For the specimen made of clay unit masonry the thickness of the floor above the ground floor amounted to 235 mm and that of the floor above the upper storey 215 mm. Figure 5 (left) shows the set-up of a test, figure 5 (right) the two specimens with the clay unit building (left) ready for testing. A detailed documentation of the instruments and measuring procedures used and their positioning is given in [1].

The pseudo-dynamic tests themselves were conducted according to the method developed at the ELSA [11]. The specimens were loaded uniaxially in the direction of the shear walls via the hydraulic pistons. Two degrees of freedom were taken into account in the pseudo-dynamic algorithm. These were the displacements at the height of the floors above the ground floor and above the upper storey respectively. The same synthetically generated earthquake, based on the same elastic response spectrum Type 1 according to Eurocode 8 (EN 1998-1 [12]) for the ground type B, such as was used for the shaking table tests at the NTU Athens [6], was taken as a basis

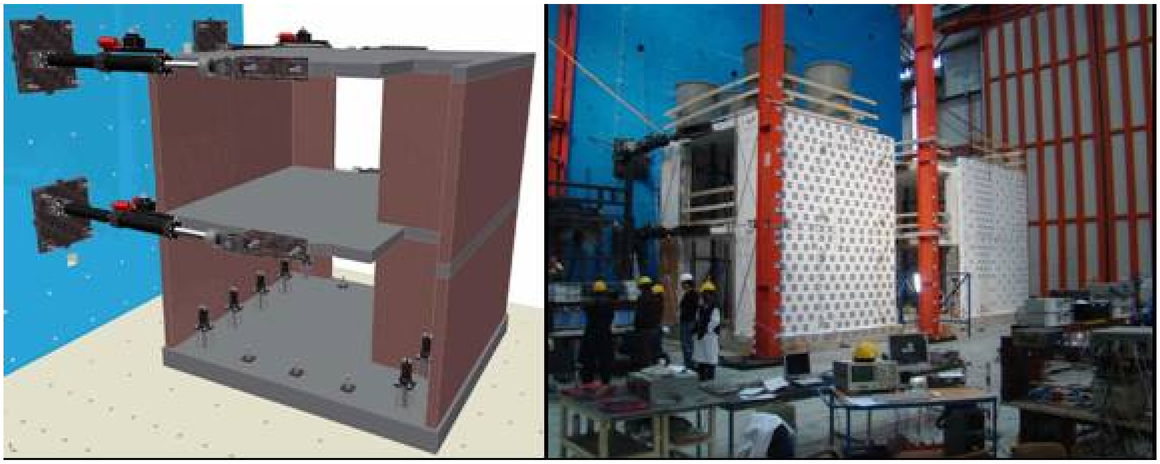

Figure 5: Specimen for the pseudo-dynamic tests; schematic diagram (left) and "ready for testing" (right)

for the algorithm. The strength, i.e. the maximum ground acceleration of the earthquake used, was increased step by step. For this purpose, with the same time course of the earthquake, the accelerations were scaled with factors. The step-wise increase of the action took place until the respective specimen showed a clear drop of horizontal resistance. Up to this point in time, each specimen had gone through several load stages (earthquakes of lower strength) without a failure of the building occurring.

PERFORMANCE FOR DESIGN GROUND ACCELERATION 0,04 G (GERMAN EARTHQUAKE ZONE 1)

Figure 6 (left) shows as an example the ground acceleration-time gradient for the test M12 on the specimen in clay unit construction. The maximum value of the ground acceleration of 0,04 g corresponds to the design value of ground acceleration for the earthquake zone 1 according to DIN 4149 [14].

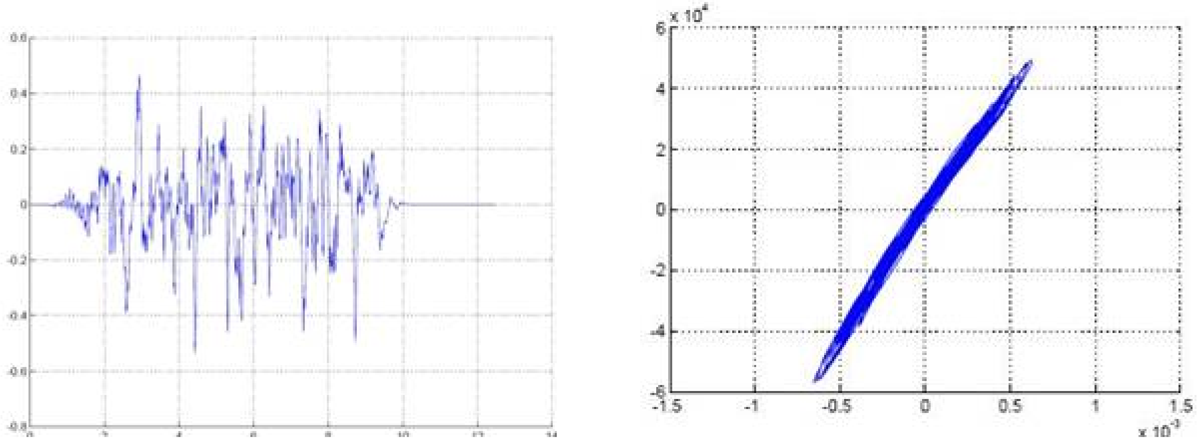

Figure 6: acceleration (m/s²)-time (s) diagram (left) and shear force (N)-interstorey-displacement (m) diagram of the ground floor (right) for ground acceleration 0,04 g

The storey displacements on the ground floor were in the region of 0,6 mm in each direction, in the upper storey at 1,0 mm. The building was crack-free; the absorbed total horizontal forces were on the ground floor between 48 and 55 kN, in the upper storey between 33 and 41 kN. The differences of the total horizontal forces as a function of the load direction are attributable to the more or less strong participation of the gable wall butt-connected to the stair well wall on the ground floor and upper storey. The shear force-storey displacement curve for the ground floor of the test M12 (clay unit specimen) are shown in Figure 6 (right). The curves are more or less linear and thus confirm the visual perception that for this load stage (this earthquake) no visible cracks have occurred. Comparable force-displacement curves resulted for the calcium silicate building (tests K); some essential test results are summarized in tables 2 and 3.

Table 2: Design ground acceleration and maximum storey displacement
(K calcium silicate unit specimen, M clay unit specimen)

Ground acceleration	Test No.	Maximum storey displacement in mm			
		Ground floor		Upper storey	
		Positive direction	Negative direction	Positive direction	Negative direction
0,04 g	K08	0,7	0,6	0,9	0,9
	M12	0,6	0,7	1,0	1,0
0,08 g	K10	2,6	1,8	2,5	2,1
	M14	2,9	2,0	3,6	2,0
0,12 g	K12	10,0	7,5	7,0	8,5
	M16	9,0	8,0	13,0	8,0
0,20 g	K16	12,0	43,0	30,0	38,0
	M20	22,0	22,0	42,0	23,0
0,22 g	M21	22,0	24,0	64,0	28,0

Table 3: Design ground acceleration and maximum horizontal force
(K calcium silicate unit specimen, M clay unit specimen)

Ground acceleration	Test No.	Maximum horizontal force in kN			
		Ground floor		Upper storey	
		Positive direction	Negative direction	Positive direction	Negative direction
0,04 g	K08	65	75	39	49
	M12	48	55	33	41
0,08 g	K10	120	120	65	80
	M14	95	120	60	75
0,12 g	K12	135	180	80	110
	M16	125	170	80	110
0,20 g	K16	130	150	90	120
	M20	120	175	85	110
0,22 g	M21	110	155	85	105

PERFORMANCE FOR DESIGN GROUND ACCELERATION 0,12 G

The maximum value of the ground acceleration of 0,12 g corresponds to the design value of ground acceleration for the German earthquake zone 3 according to DIN 4149 [14], in regions with the most unfavourable subsoil conditions (C-R).

The maximum storey displacements on the ground floor were between 8 and 9 mm, in the upper storey between 8 and 13 mm. The absorbed total horizontal forces were on the ground floor between 125 and 170 kN and in the upper storey between 80 and 110 kN.

From the preliminary tests in Pavia a maximum storey bearing capacity of 90 kN (50 kN from the shear wall at the stair well and 20 kN each from the exterior walls) would have been expected. Apparently, further positive building effects (participation of combined cross-sections, load redistributions from the perpendicular walls) exist here, which considerably increase the bearing capacity of the building and are not taken into account so far in the design.

The shear force-storey displacement curves of the test M16 (clay specimen at 0,12 g) for the ground floor and first floor are shown in Figure 7. The curves have a clearly bilinear gradient. With increasing storey displacement the absorbable horizontal force continues to rise distinctly. Horizontal cracks were observed in the terraced house partition walls as well as a rotation of the shear walls with gaping joints at the wall head and wall foot combined with fine cracks along the horizontal joints. The horizontal joint cracks closed again however at the end of the test and were then no longer visible.

By reaching this load stage the verification was already provided that this building type is absolutely suitable for the German earthquake zone 3 even with the most unfavourable subsoil conditions.

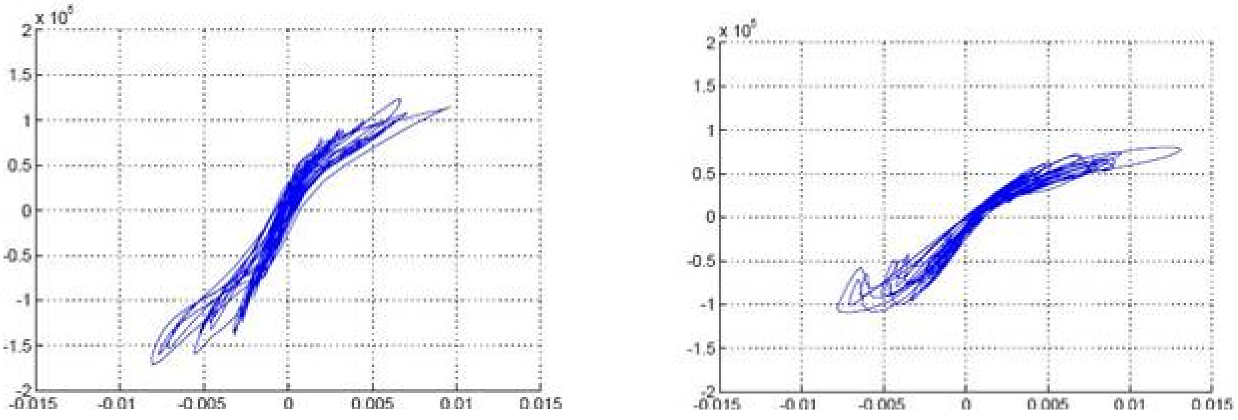

Figure 7: Shear force (N)-interstorey-displacement (m) diagrams of ground floor (left) and first floor (right) for the ground acceleration of 0,12 g.

Additional tests were carried with both specimens with the characteristic central European earthquake, in order to get an impression of the behaviour for higher design ground accelerations. The design ground acceleration was increased in steps of 0,02 g until a severe deterioration of the building with endangering of the measuring devices during the following quake could not be ruled out.

PERFORMANCE FOR DESIGN GROUND ACCELERATION 0,20 G

The last earthquake to be absorbed without major damage in the shear walls corresponded to a ground acceleration of 0,2 g. The maximum storey displacements lay on the ground floor between 22 and 23 mm, see figure 8, in the upper storey between 22 and 42 mm. The larger displacement in one direction in the upper storey was attributable to a crack along the horizontal joints in one exterior wall.

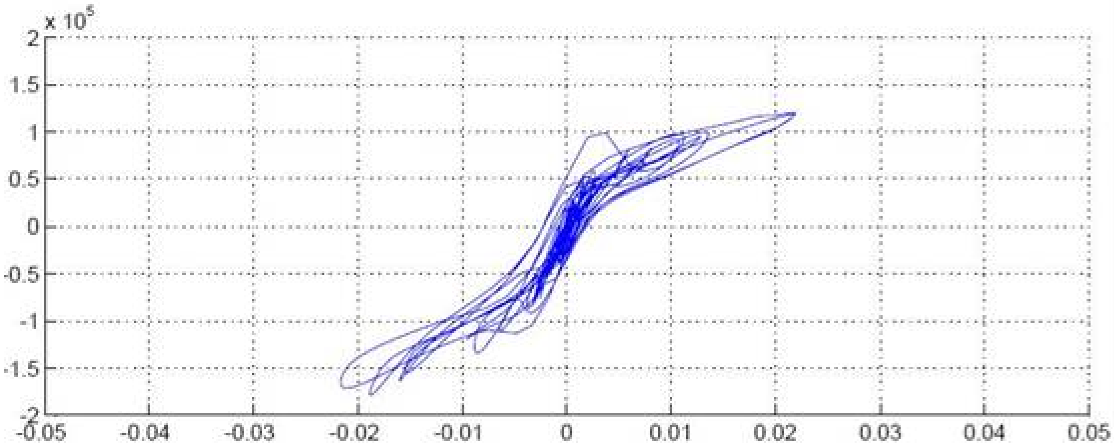

Figure 8: Shear force (N)-interstorey-displacement (m) diagram (ground floor) for the ground acceleration 0,20 g

Figure 9: Crack pattern of shear walls after the test with ground acceleration 0,22 g; main shear wall ground floor (left), external wall ground floor (centre) and external wall first floor (right)

In the shear walls on the ground floor, fine step-shaped cracks following the horizontal and vertical joints were recognizable; however the absorbed total horizontal forces with 120 to 175 kN on the ground floor and 85 to 110 kN in the upper storey were still significantly higher than would have been expected after the preliminary tests.

The test was stopped after the 0,22 g earthquake due to severe damage in the external walls in the first floor, see figure 9.

SUMMARY AND CONCLUSIONS

The large-scale pseudo-dynamic tests on terraced house halves carried out at the ELSA research laboratory in Ispra have shown that this typical German building type has a sufficiently high resistance in case of earthquake loads. This resistance is extremely underestimated with the design methods currently applied. A detailed documentation on this subject is given in [15] in these proceedings. The discrepancy shown is essentially attributable to two factors:

- On one hand force-based design models do not take the behaviour of masonry in the case of an earthquake sufficiently into account and this can not be compensated with the currently applied behaviour factors q.

- On the other hand the tests showed clearly that the usually assumed cantilever model is not appropriate for the design of masonry buildings with reinforced concrete slabs as the shear walls failed on first floor and not on ground floor.

As a consequence, the currently applied design models for masonry must be reviewed and optimized and in particular deformation-based design procedures should be authorized for the verification of buildings in German earthquake regions. In force-based design with simplified procedures, the load bearing and deformation behaviour of load bearing masonry buildings must be covered by adapted behaviour factors and/or the introduction of building (overstrength) factors, in order to make the obvious structural reserves utilizable in design.

The implementation of the findings from the ESECMaSE research project can only take place if these are included in the short term in the standardization procedure. This concerns both the national design standards for earthquakes and masonry as well as the corresponding European standards. This implementation must be speeded up emphatically by the masonry industry in order to reduce the existing unjustified competitive disadvantages of masonry in this sector.

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