Testing unreinforced masonry structures at reduced scale

15 WCEE
LISBOA 2012

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SUMMARY:
When testing multi-story structures on a shaking table, most testing facilities require a reduced scale model. Producing scale test units at small scale is particularly challenging for unreinforced masonry structures. Previous work by other researchers showed that scaling of units and mortar joints is mandatory in order to obtain for the reduced scale masonry failure modes, which are similar to those of the full scale masonry. However, even if the size of bricks and the thickness of mortar joints are reduced correctly, the reduced scale masonry tends to be too strong but also too flexible. In case of hollow bricks, scaling becomes even a greater challenge.

As preparation for a 1:2-scale shake table test of a modern 4-story building comprising unreinforced masonry walls, this paper presents an overview of the difficulties related to scaling. Furthermore, first experimental test results on comparing full- and half-scale masonry are presented and analyzed.

Keywords: Scaling effects, Unreinforced masonry, Seismic testing

1. INTRODUCTION

In civil engineering, a general problem in experimental testing is the size of the specimen: the examined structures are normally of such large dimensions (houses, bridges, etc.) that it is usually impossible to test an entire structure at full-size. In consequence, either only parts of the whole structure are tested or the models are scaled down to a maximum feasible size. Often, a combination of both is required to optimize cost and to obtain proper results.

In the framework of the research performed at the Earthquake Engineering and Structural Dynamics Laboratory at EPFL, Switzerland, a shake table experiment is planned for autumn 2012. The test itself will be conducted on the shake table of the TREES Laboratory in Pavia, Italy. The test specimen will be a four-story structure consisting of six URM walls and two RC walls. These walls will be coupled horizontally by a RC slab at each floor level. On one longitudinal side, the coupling effect of the slab will be amplified by spandrel elements. The aim of this research is to investigate the coupling influence and interaction between the different kinds of structural elements. For this reason, it was favored to scale the whole structure by a factor 1:2 instead of investigating solely parts of the whole structure. Thus, special attention has to be drawn to the scaling of the different materials in order to reproduce a correct interaction between the RC and URM elements at 1:2-scale.

The aim of this article is to give the reader an introduction to the upcoming problems when using small scale experimental tests of masonry structures for predicting their behavior in earthquake engineering. Some solutions are presented and their feasibility and application limits.

2. DIMENSIONING REQUIREMENTS FOR SHAKE TABLE SPECIMENS

2.1. DIMENSIONAL ANALYSIS FOR THE HALF SCALE SPECIMEN

The aim of physical testing is to gain an idea about the prototype's behavior under real loading conditions and to obtain a correct prediction for its response in form of displacements, strength, elastic behavior, etc. In a reduced scale specimen, the scaling might affect its physical properties and it is important to understand these changes in order to draw correct conclusions on the prototype behavior. Different theoretical scaling models have been developed for seismic testing. The most important ones are summarized in Tab. 1.1.

Table 2.1. Scale factors for the different models (S_i is the scaling factor for the equivalent variable $i = i_{prototype} / i_{model}$) , e.g., (Tomaževič & Velechovsky, 1992; Krawinkler, 1979).

		Model Type				
		Modified materials		Prototype materials		
		True Replica Model	Complete Model	Artificial Mass Simulation	Simple Model	Gravity Forces Neglected
Length	l	S_l	S_l	S_l	S_l	S_l
Time	t	$\sqrt{S_l}$	$\sqrt{S_l}$	$\sqrt{S_l}$	S_l	S_l
Frequency	f	$1/\sqrt{S_l}$	$1/\sqrt{S_l}$	$1/\sqrt{S_l}$	$1/S_l$	$1/S_l$
Velocity	v	$\sqrt{S_l}$	$\sqrt{S_l}$	$\sqrt{S_l}$	1	1
Gravity	g	1	1	1	S_l	neglected
Acceleration	a	1	1	1	$1/S_l$	$1/S_l$
Mass density	ρ	S_E/S_l	1	*)	1	1
Strain	ϵ	1	1	1	1	1
Stress	σ	S_E	S_l	1	1	1
Strength	f_u	S_E	S_l	1	1	1
Mod. of elasticity	E	S_E	S_l	1	1	1
Displacement	Δ	S_l	S_l	S_l	S_l	S_l
Force	F	$S_E S_l^2$	S_l^3	S_l^2	S_l^2	S_l^2
*) For lumped masses: $S_M = S_l^2$						

The True Replica Model and Complete Model approach consists in fulfilling all scaling requirements without producing distortion by the scaling (Krawinkler, 1979; Tomaževič & Velechovsky, 1992). Their inconvenience relates to the required scaling of the material properties (True Replica Models) and the required modification of the gravity constant (Complete Models), e.g. see Tab. 2.1.

2.2. ARTIFICIAL MASS SIMULATION

Usually, it is better to accept a limited distortion in the modeling, rather than to complicate the testing. Therefore, Adequate Models were developed: Artificial Mass Simulation and Models with Neglected Gravity Force (Moncarz & Krawinkler, 1981; Krawinkler & Moncarz, 1982). In Lumped Mass System (Krawinkler, 1979), a sub-form of Artificial Mass Simulation systems, mass is added in the form of concentrated masses at certain places of the structure, e.g., at the floor level, and the requirement of the similitude of the material properties is decoupled from the scaling of the length. It is important that the added mass is non-structural in order to maintain the same structural behavior.

The scaling requirement for the total model mass S_M is obtained from Cauchy's formula for a correct simulation of the inertia forces (Krawinkler, 1979):

$$\left(\frac{gM}{l^2 E}\right)_{prototype} = \left(\frac{gM}{l^2 E}\right)_{model}$$

$$\frac{S_g S_M}{S_E^2 S_l} = \frac{S_M}{S_l^2} = 1 \Leftrightarrow S_M = S_E S_l^2$$

where S_a represents the scaling factor for the ground acceleration a, S_E the scaling factor for the E-modulus and S_l represents the scaling factor for the length l.

Adding lumped masses affects the dynamic response of the structure. For cases where the additional mass gets too big in comparison to the structural mass, Krawinkler (1979) recommend distributing the added mass (Distributed Mass System). The necessity of distribution depends on the specific case, but especially on the simulated modes of deformation. If, for example, the floors are not rigid enough and their flexural deformations contribute to a notable part to the total energy dissipation, it might be necessary to distribute the mass over the whole floor area, see e.g. Moncarz & Krawinkler (1981), Krawinkler & Moncarz (1982).

3. RELEVANT SIMILARITIES FOR A PROPER REPRODUCIBILITY IN SMALL-SCALE MASONRY IN SEISMIC TESTING

In the previous section the theoretical models for scaling were summarized. According to these models it is sufficient to scale down all properties according to the model rules in order to obtain a good reproduction of the full-scale behavior. However, in reality, it is rather difficult to obtain the same behavior for the model masonry as for the prototype behavior. In order to be able to decide which simplifications are acceptable, Tomaževič and his co-workers named three similarities to be the most important ones for experimental testing of masonry in earthquake engineering (Tomaževič , et al., 1990; Tomaževič & Velechovsky, 1992):

- Similarity in mass and stiffness distribution

The similarity of mass and stiffness distribution is important for the similitude of the dynamic response (Tomaževič , et al., 1990; Tomaževič & Velechovsky, 1992).

- Similarity in failure mechanism and damage pattern

Especially when structures are tested until failure, which is often done in earthquake engineering, it is important, that model and prototype have the same behavior in the inelastic domain. It is also important to simulate the correct failure mode in order to obtain the correct displacement capacities of the elements (see Sec. 1.1 and energy dissipation during the dynamic response (Tomaževič, 1987; Tomaževič & Velechovsky, 1992)).

- Similarity of the stresses

In order to obtain failure at the same loading stage, but especially to obtain the same failure mechanism (Tomaževič & Velechovsky, 1992), it is important to generate the same stresses and strengths in the model as in the prototype. Tomaževič tested the capacity of URM piers for dynamic and static lateral loading under different loading conditions and emphasized the influence of the mean vertical stress on failure mode and thus, on capacity (Tomaževič, 2000).

4. CONSEQUENCES FOR EXPEREMENTAL SMALL-SCALE TESTING OF MASONRY STRUCTURES

In the precedent sections different basic issues concerning the scaling in experimental testing have been summarized. In the following parts these basics will be discussed with respect to the different components of masonry.

4.1. SCALING EFFCTS ON BRICK UNITS

There exist different ways to manufacture a reduced-sized model brick. Replacing the model brick by a smaller brick of a different material proved to be complicated (Tomaževič, 1987) and should be avoided, since it is difficult to quantify the exact distortions introduced by the different material.

Also the reproduction of solid model bricks at smaller size proved to be complicated. In Egermann et al. (1991), the solid model blocks were produced individually at correct size with identical material. Prototype series and half scale series were manufactured in the same plant, while a quarter scale series was manufactured in another plant with reduced burning temperature. Comparison of the first two series showed that the smaller brick was stronger than the larger one. However, in the third series, for which the temperature was reduced, the obtained strength was too small. Mohammed (2006) and Mohammed et al. (2011) report the same problems of dissimilarity of strength for bricks of smaller size burnt at the same temperature.

Another way of producing small scaled bricks is to cut them down from prototype bricks after burning. Even though good experiences were obtained with the use of cut model bricks (Tomaževič , et al., 1990), some difficulties might appear. For instance, Mohammed (2006) mentioned for solid bricks, the importance of the orientation of the loading and the cut compared to the original brick. Also the roughness of the cut surface should be considered (Davies, et al., 1995), since it determines the shear resistance of the mortar-brick interface. Normally in the production, bricks are wired-cut before firing. If smaller bricks are cut from full-scale bricks after they were fired, the surface properties including the roughness change.

In addition to the general properties of scaled bricks, hollow clay units feature further specific properties that have to be also considered, for instance, its anisotropic behavior. In general the vertical compression strength is mainly influenced by the net area of the bricks and not by the shape of the perforation (Ganz, 1985). In case of seismic loading, masonry elements are also subjected to loading in the horizontal direction and hence, also the horizontal in-plane properties, like shear strength and horizontal compression strength of the bricks are important (Ganz, 1985). While the shape of the perforation is not decisive for the vertical properties, it has a significant influence on the horizontal ones. Lourenço et al. (2010) determined for in-plane continuous and straight webs and shells (mostly the case for the rectangular perforation), that the compression strength of the brick in horizontal in-plane direction was significantly higher than for other bricks with rice-shaped holes. During seismic loading the in-plane shear resistance is important, hence, the webs and shells should be continuous in the in-plane direction of the walls, see also Ganz (1985), Mann et al. (1990) and Beyer et al. (2010).

It was mentioned above, that several researchers had difficulties to obtain identical properties when bricks were fired at smaller size, e.g. Mohammed (2006). It should be noted here, that these difficulties appeared always for solid bricks, where the total size is important for the development of temperature in the center of the brick during the burning process. For hollow bricks, when the thicknesses of web and shell are chosen to be identical for the prototype and the model brick, it is expected that the differences should not be so important.

4.2. SCALING EFFECTS ON MORTAR AND JOINTS

The sucking behavior of the bricks is the main mechanism, which affects the mortar properties and the characteristics of the joint-brick interface. In the literature it is often mentioned that for thinner joints the suction of the brick is more important, e.g. Drysdale and Hamid (2008). Thus, the water-cement ratio in the mortar is changed and the crystallization process in the mortar is modified. It is, however, difficult to quantify this effect. If the water-cement ratio is only slightly reduced, the strength in the mortar should increase, since more cement can solidify. If too much water is sucked from the mortar, it might appear that there is not enough water left for the mortar to crystallize completely. Hence, dependent on the amount of adsorbed water, the strength of the masonry will either increase or decrease (Mohammed, 2006).

The influence of the sucking behavior of bricks was investigated by several researchers. For instance, Brocken et al. (1998) noted that pre-wetting of bricks affects the suction process only in a significant matter, if the water content of the brick reaches nearly saturation. Also the use of water retention products was mentioned to be difficult: it is noted that the addition of water retention products does not influence the quantity of water extracted, but slows down the suction significantly (Brocken, et al., 1998). Also Green et al. (1999) mentioned that only big quantities of water retention would show significant changes in sucking behavior.

Nevertheless, Egermann et al. (1991) obtained a similar strength for the model masonry as for the prototype masonry. In contrast, they noted a reduced stiffness for the model masonry in comparison with identical full size masonry. This effect was attributed to the reduced weight on the bed joints during curing. However, Egermann et al. (1991) reduced for their experiments the size of the aggregates in the mortar, what might have also caused a softening in the scaled masonry structures.

5. OBTAINED SIMILARITIES FOR MODEL BRICK IN COMPARISON TO PREVIOUS WORK

Even though it is foreseen to use identical materials at full and reduced scale, the literature review in the previous sections showed that it is not straightforward to obtain the same properties for prototype and model masonry. Accordingly, it was decided to match first each component of the masonry, i.e., brick unit and mortar joint, and to assess thereafter the behavior of the masonry.

5.1. COMPARISON BETWEEN PROTOTYPE BRICK AND MODEL BRICK

According to the results of the literature review, the following properties are judged as particularly important for a good similitude:

- Similar material properties imply two conditions: (1) a similar basic material should be used (Tomaževič, 1987) and (2) the drying and burning procedure should be similar in order to obtain the same properties for the burned clay material, e.g. Mohammed (2006).

- Similar void ratio is important in order to obtain similar compression strength parallel to perforation, e.g. Ganz (1985). To obtain similar strength in horizontal in-plane direction, it was decided to consider also the effective section in this direction. Thus, the ratio of the sum of the web and shell thicknesses to the total width of the bricks was compared.

- Similar surface properties of the bricks in relation to the size of the aggregates in the mortar (Davies, et al., 1995).

To obtain similar material properties, the model brick was produced at the same plant as the prototype brick. Thus, both bricks are produced of the same clay and can be burned using the same procedure.

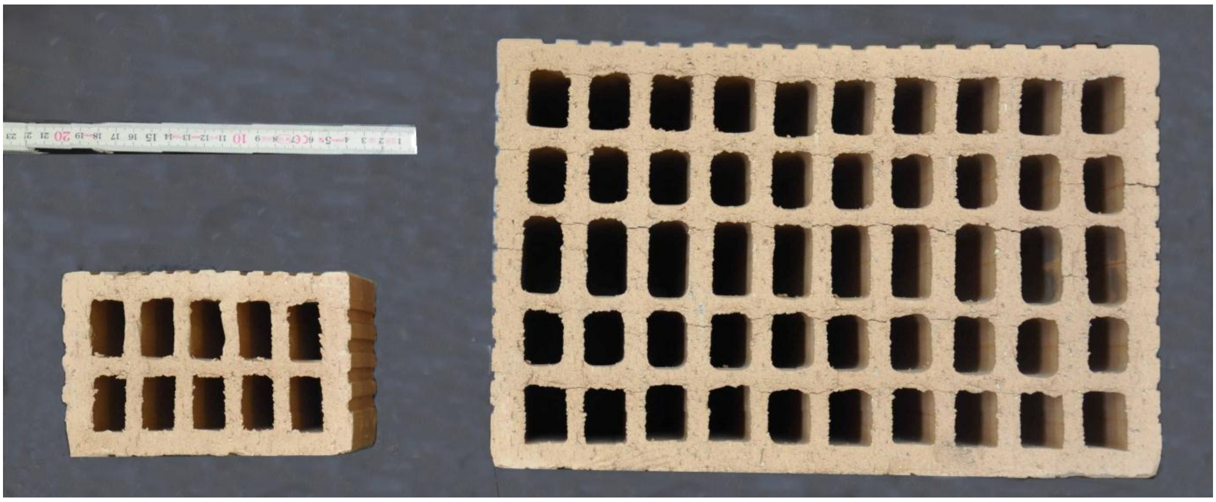

Figure 5.1. Final prototype and model brick: Model brick type M3, cut out from ME 10 without tongue and groove and Prototype brick P3, modified ME 20 without tongue and groove from Morandi SA, Switzerland.

In general, two options exist for scaling the hole layout of a brick respecting similarities of void ratio: (1) the geometry is completely scaled, including web and shell thicknesses, or (2) shell and web thicknesses remain identical and the number of rows of holes is decreased. Reduced thickness of webs and shells causes differences during the drying and burning process. Clay bricks are not a perfect homogeneous material but have a certain quantity of micro cracks, which develop during the drying and burning process. It is assumed that the onset of failure of the bricks is caused by these micro cracks, similarity should also be given in the ratio of crack size to web and shell thickness. Thus, the second option for the scaling of the hole layout was chosen.

In total, two kinds of prototype bricks and four kinds of model bricks were investigated. First, dimensions and weights were determined for all bricks. Then, the bricks were tested under compression in both in-plane directions (parallel and perpendicular to perforation). Furthermore, the flexural tensile strength in the horizontal in-plane direction was determined from 3-point bending tests. Herein, only the chosen prototype and model brick are discussed and shown in Fig. 2.1. Table 5.1 illustrates the results for the two chosen bricks.

Table 5.1. Properties of chosen bricks P3 and M3

		Prototype brick P3	Model brick M3
Average dimensions of a brick			
Length	mm	297	148
Width	mm	194	96
Height	mm	189	94
Average mass and density of a brick			
Mass	kg	9.9	1.3
Volumic mass	kg/m^3	901	996
Void ratios and effective length / width of a brick			
Void ratio	-	49.3	39.5
Effective length*	-	30.6	37.8
Effective width*	-	28.9	36.5
Average strength and deviation			
Compression, parallel to perforation	MPa	35.0 ± 7%	33.3 ± 25%
Compression, perpendicular to perforation	MPa	9.4 ± 8%	10.8 ± 17%
Tensile strength, perpendicular to perforation	MPa	1.27 ± 38%	1.61 ± 41%
*The effective length / width describe the percentage of filled material to voids over the length / width.			

Prototype and model bricks come from the same manufacturer Morandi SA, Switzerland. Hence, the same initial clay mixture was used for the production. Furthermore, both bricks contain similar web and shell thicknesses. Thus, the same burning procedure was chosen for. Void ratio and effective width showed small differences, which resulted also in small differences in compression strength and average volumic mass of a brick. Only the tensile strength is significant higher (around 25%) for the 1:2-scale brick, than for the 1:1-scale brick. Nevertheless, differences of strength were small compared to the variation of the results and the similarities between both bricks were considered as satisfactory.

Both bricks were cut before drying and burning, hence, similar surface properties were obtained. However, in our case it was foreseen to use similar mortar with same size of aggregates. Therefore, similar surface properties should cause similar friction values at the interface mortar / brick.

5.2. COMPARISON OF MASONRY TRIPLETS IN FULL SCALE WITH HALF SCALE TRIPLETS

The literature review revealed the difficulties associated with scaling of the mortar joint thickness caused by the sucking behavior. Thus, in addition to the unit, also the mortar joint needs to be investigated. In order to quantify the influence of scaling, first a series of triplets for each size with identical mortar mixture was produced. Furthermore, a series at 1:2-scale was constructed with mortar containing a commercial water retention product.

For each series, six columns composed of three bricks were produced the same day. They were built as it is usually done in praxis: first a thick layer of mortar was applied on the lower brick and the thickness of the mortar layer was assured by hammering on the upper brick until the wished thickness was reached. For reasons of reproducibility, it was decided not to wet the bricks before applying the mortar joint. The uprightness of the columns was controlled with the help of a water level and the resulting thickness was measured after curing. The triplets cured between 21 and 23 days until they were tested under uniform compression as shown in Fig. 5.2. The load introduction at top and bottom of the triplet was provided with a fast curing cement layer put between two plastic sheets. The loading velocity was chosen in such a way that the failure occurred after 15 to 20 min after the beginning of the loading. The results of the compression strength are shown in Fig. 5.3. (a).

Figure 5.2. Unidirectional compression test on one 1:2-scale masonry triplet.

As mortar, a so-called WEBER MUR Maxit 920 mixture was taken. This mortar corresponds to a commonly used mortar mixture in Switzerland and contents already the necessary cement and sand.

The amount of water was fixed for all mixtures at 5.5 liters per bag of 30kg of cement, which corresponds to 10% more water content as the recommended quantity. This quantity of water was fixed at an earlier stage in collaboration with an experienced mason. The water retention was added as liquid directly to the water before mixing the mortar. In this series, 0.4 liters of water retention liquid was added to 1.0 liter water, which corresponds to four times the quantity recommended by the manufacturer. During the construction of the masonry triplets, 160mm x 40mm x 40mm mortar samples of each mortar mixture were taken and put to harden in styrofoam formwork. All samples were stored with the masonry triplets in order to simulate similar drying conditions. The mortar cubes were tested at the age of 24 days for their flexion tensile strength and compression strength. The results are illustrated in Fig. 5.3.b according to the corresponding testing series.

Figure 5.3.a shows the drawback of the scaling of masonry. Identical mortar and bricks with similar compression strength were taken, nevertheless, an increase of more than 80% can be observed for the 1:2-scale triplet with identical mortar. In masonry, the compression failure is also dominated by the tensile strength of the brick unit, e.g. Hilsdorf (1969). But the recorded increase of tensile strength was only of 25% (see previous section) and does not explain the high differences between the compression capacity at 1:1- and 1:2-scale. This discrepancy corresponds also to previous studies, for instance Mohammed (2006), who explains the origin of the differences with the different sucking behavior.

For the 1:2-scale triplets built with mortar containing water retention, the compression strength increases by a similar value than the other small scale triplets. Brocken et al. (1998) and Green et al. (1999) report difficulties in compensating the scaling effect on the sucking behavior of the masonry by using water retention. Indeed, in our case the water retention improved the mechanical properties of the mortar alone (see Fig. 5.3.b), but did not modify significantly the compression strength of the 1:2-scale triplets (see Fig. 5.3.a). The mortar cubes were stored with the triplets during the whole curing phase, and not put to dry in a climate chamber at early age. The water retention could avoid early drying of the mortar cubes in the first days of curing, without affecting the physical phenomena of water suction which occurs when wet mortar is put in contact to dry bricks. However, when we compare the trend lines corresponding to both 1:2-scale masonry triplet, a significant change of slope in dependence of joint thickness can be recognized.

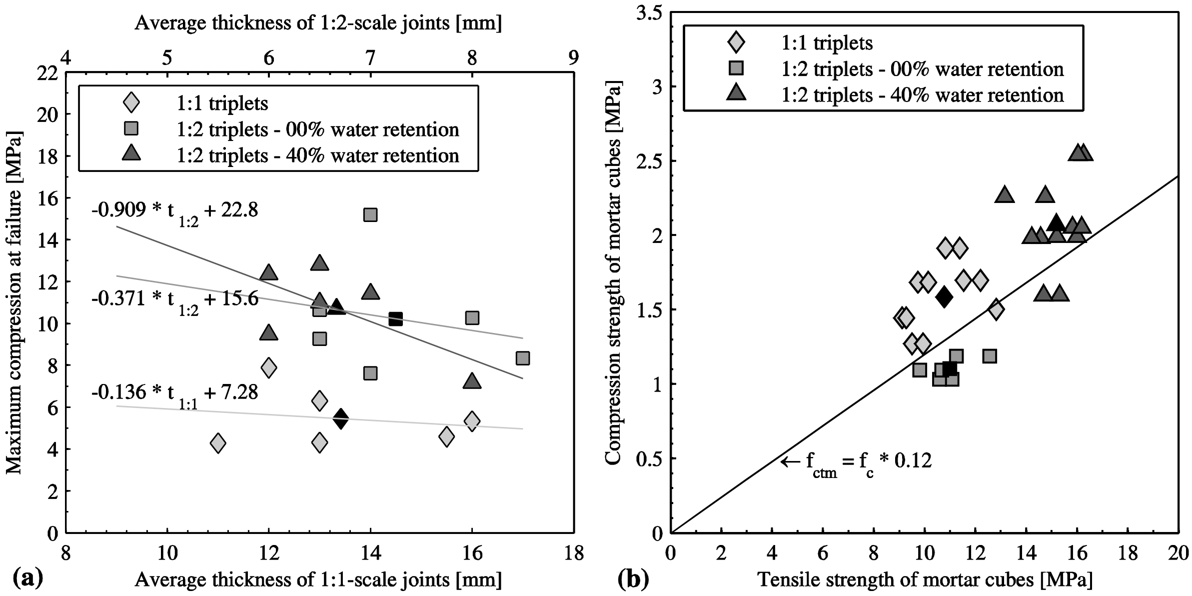

Figure 5.3. Results from tested masonry triplets and mortar cubes at 1:1- and 1:2-scale. The results of each specimen of a series are presented in grey and the average value for each series in black: **(a)** Compression capacity of triplets in dependence of average thickness of the joints with the corresponding linear trend line for each series (x-axes at bottom valid for 1:1- and x-axes at top valid for 1:2-scale masonry) **(b)** Tensile strength of mortar in dependence of compression strength.

6. CONCLUSIONS AND FURTHER FORESEEN INVESTIGATIONS

The aim of the 1:2-scale test of a 4-story structure on a shake table test is to investigate the interaction between different structural elements in a mixed structure composed of URM and RC elements. While for RC structures it is generally accepted that scaled elements reproduce well the behavior of equivalent prototype structures, this is not the case for URM structures: the literature review revealed the difficulties when reduced scale masonry has to be used.

According to the nature of masonry, it was decided to avoid distortions by choosing the right component for the model masonry. Thus, the model brick and the small scale mortar joint were identified, which should produce the smallest distortions. For the choice of the brick, it was noticed that in addition to the manufacturing process, special care should also be taken to ensure the same void ratio and web shell thickness. Therefore, the term ‘effective thickness’ was introduced. When these rules were observed, the prototype and the model brick were found to have similar mechanical properties. For the choice of the ideal mortar, investigations were started and three different series of triplets at both scales were built and their compression strength was compared. The tests confirmed the conclusions obtained from the literature review and revealed, furthermore, the difficulties of compensating these scaling effects on the joints.

According to the results of the initial investigations, further studies concerning the “perfect” mortar at model scale will be performed. Furthermore, it was concluded that tests on bigger specimen will be necessary to provide a detailed comparison of mechanical properties of full and reduced size masonry. This comparison will further help to draw correct conclusions for real size structure with the results obtained from the proposed shake table test on the half scale masonry structure.

ACKNOWLEDGEMENT
The authors would like to thank Morandi Frères SA, Switzerland, for the donation of the bricks.

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