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SOME ASPECTS OF EXPERIMENTAL TESTING OF SEISMIC BEHAVIOR OF MASONRY WALLS AND MODELS OF MASONRY BUILDINGS

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ABSTRACT

Some aspects of experimental testing of seismic behavior of masonry walls and models of masonry buildings are discussed. In order to experimentally simulate the observed failure mechanisms and determine the parameters of seismic resistance, masonry walls of similar geometry and restraints as in the building's structural system are tested by subjecting them to similar loading conditions as they are subjected to in a building during an earthquake. It has been shown that the test results depend on the shape and velocity of application of induced lateral load patterns used to simulate the seismic loading. Seismic behavior of masonry buildings can be studied by testing the small-scale models of buildings on simple earthquake simulators. However, since scale effects represent a difficult problem to solve, the overall seismic behavior of structural systems only can most often be studied, and not the behavior of structural details.

KEYWORDS: Masonry Wall, Small-Scale Model, Testing, Seismic Behavior

INTRODUCTION

Masonry is a typical non-elastic, non-homogeneous and anisotropic building material, which consists of masonry units, mortar and grout, and steel reinforcement. Consequently, when subjected to lateral loads, masonry structural elements do not behave elastically even in the range of small deformations. Moreover, different masonry construction systems, such as plain, confined and reinforced masonry, exhibit different behavior when subjected to seismic loads. Therefore, the equations and numerical models which are based on the theory of elasticity and are commonly used in the analysis and design of other types of structures, should be modified by taking into consideration the specific characteristics of masonry materials and structural behavior. In order to adequately model the actual seismic behavior of each specific type of masonry construction systems, experiments are needed. The input parameters, which are used in the calculations, should also be determined by tests which are compatible with the experiments on the basis of which the mathematical models have been developed.

Recently, masonry is undergoing transition from traditional handicraft to modern engineered building material. Masonry buildings, which have been built for many centuries according to builders' experience and by taking into account simple rules of construction, are nowadays designed by methods of engineering and are built according to building codes on an equal basis with buildings made of modern structural materials. This has become possible due to considerable experimental and theoretical research in the behavior of masonry walls and buildings subjected to seismic actions, which has been carried out in many countries in the last several decades.

It is not the aim of this contribution to present the state-of-the-art report on testing methods used in the laboratories world-wide. Laboratory testing of basic material properties is also not part of the discussion of this paper. Some aspects of experimental simulation of seismic behavior of masonry structures only will be discussed and some problems related with testing will be pointed out on the basis of experience obtained at the Slovenian National Building and Civil Engineering Institute (ZAG) in Ljubljana, Slovenia, where experimental research in seismic behavior of masonry structures has been one of the major concerns in the last several decades.

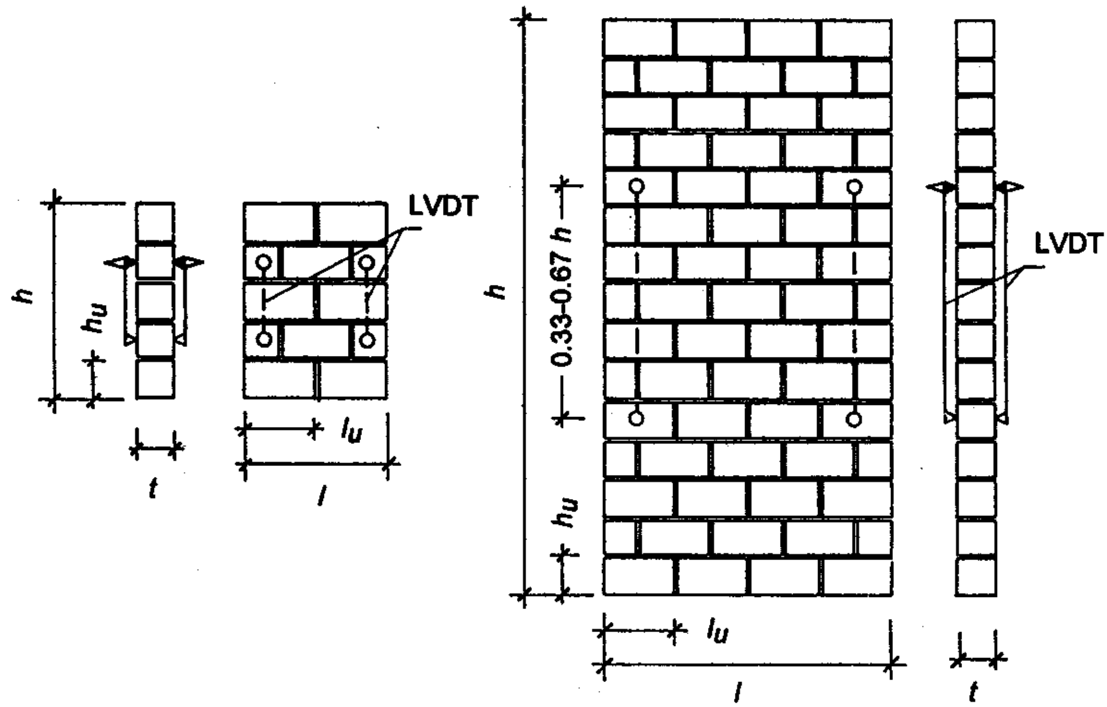

Fig. 1 Masonry specimens for compression tests (EN 1052-1)

TESTING OF MASONRY WALLS

Either physical mechanism models or finite element methods can be used as a basis for calculation algorithms, which simulate the behavior of masonry walls and structures when subjected to seismic loads. Although good results are obtained for the specific cases, simulating the situation for which the models have been developed, sophisticated models are in most cases not suitable for practical use. Therefore, average values of sectional forces, stresses and strains are determined, based on the gross cross-sectional characteristics of the walls. Simple models and equations based on the theory of elasticity are used, modified to take into account the inelastic, non-homogeneous and anisotropic character of masonry as structural material.

In these equations, the following parameters which define the mechanical characteristics of masonry as structural material, are used:

- compressive strength f and tensile strength f_t, which define the strength of masonry,
- modulus of elasticity E and shear modulus G, which define the deformability of masonry in the linear range,
- ductility factor μ, which defines the displacement capacity of a masonry wall element.

Whereas the strength and deformability parameters represent the intrinsic mechanical properties of the masonry, the ductility factor is a typical mechanical property of a masonry wall. It cannot be attributed to the masonry alone.

Standardized testing procedures are used to determine the compressive strength f and modulus of elasticity of masonry (for example procedures as specified in standard EN 1052-1), by using either small wallets or walls (Figure 1). Stress-strain relationships of masonry at compression also are obtained by these tests (Figure 2).

In order to determine the parameters of seismic resistance, the observed failure mechanisms of masonry walls after earthquakes are simulated in the laboratory. For this purpose, masonry walls of similar geometry and restraints as in the building's structural system are tested by subjecting them to similar loading conditions as they are subjected to in a building during an earthquake. Shear behavior of the walls is defined by the values of f_t and G. Therefore, diagonal compression tests, simple monotonic or cyclic racking tests are used for their determination. As some correlation studies have shown (Bernardini et al., 1980), either way, similar values of tensile strength can be obtained.

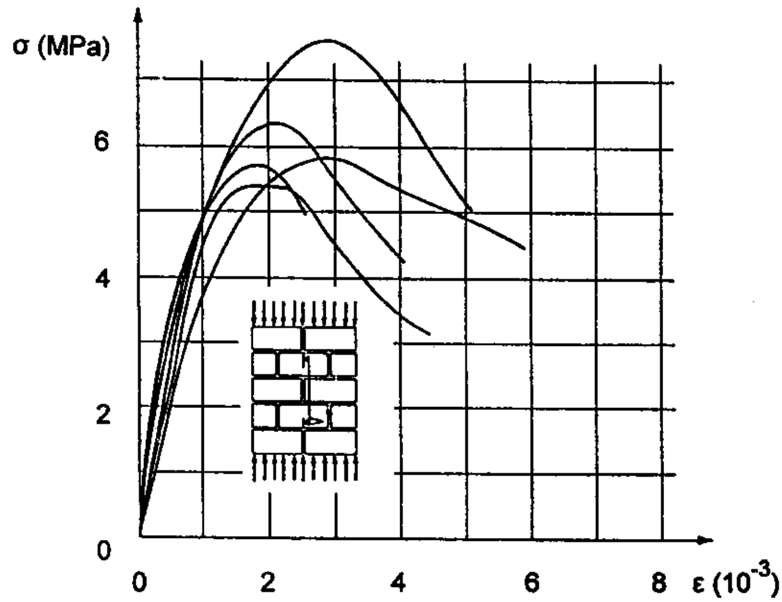

Fig. 2 Typical experimental stress-strain relationship of masonry at compression (Tomaževič and Žarnic, 1984)

However, resistance capacity of masonry structures in seismic conditions is also influenced by other parameters, such as ductility and energy absorption capacity, as well as phenomena of strength and stiffness degradation and deterioration. These parameters can be evaluated only by testing the specimens under similar cyclic loading conditions as they are subjected to during earthquakes in actual buildings (Figure 3). Various testing devices and various cyclic lateral load patterns, applied statically or dynamically, are used to simulate the seismic loads in different research laboratories

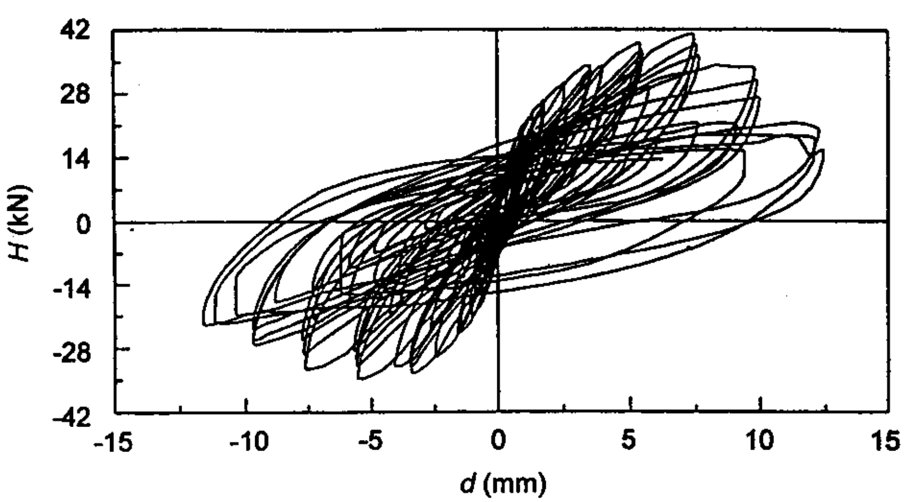

Fig. 3 Typical lateral load - lateral displacement relationship, obtained by cyclic lateral resistance test of a masonry wall

1. Boundary Restraints

It is, however, quite difficult to exactly simulate the real boundary conditions. In the buildings, fixity conditions may change during the earthquake due to progressive damage and consequent changes in rigidities of the wall and surrounding structural elements. Being part of the shear-wall of the building structure, additional vertical stresses develop in the wall because of prevented rotation when subjected to lateral load. Since the real situation in the buildings is difficult to simulate and in order to avoid any uncertainties, which would prevent accurate evaluation of the measured parameters, tests are carried out under the simplified and controlled boundary conditions. Usually, vertical load is kept constant during the test, whereas boundary conditions are controlled by means of specially designed mechanical systems. To eliminate errors, displacements and rotations of supporting system are measured during the tests.

In Ljubljana, the walls are tested either as symmetrically fixed or as simple vertical cantilevers. In the first case, the specimen is placed on a steel beam, laterally supported by prestressed dynamometers. Constant vertical load is induced by a pair of hydraulic jacks, fixed below the testing floor and connected to a gas accumulator. Vertical load is transferred to the upper parallelogram by means of steel rods. The parallelogram is moved laterally according to a programmed displacement pattern by means of a programmable hydraulic actuator (Figure (4a)).

In the second case, however, the foundation block on which the specimen is built, is fixed to the testing floor. Constant vertical load is induced by a hydraulic jack, connected to a gas accumulator, whereas lateral load is imposed by means of a programmable hydraulic actuator, fixed to the upper beam of the specimen. Rollers are placed between the steel plates on the top of the specimen below the jack to allow for the free motion of the wall during cycling (Figure (4b)).

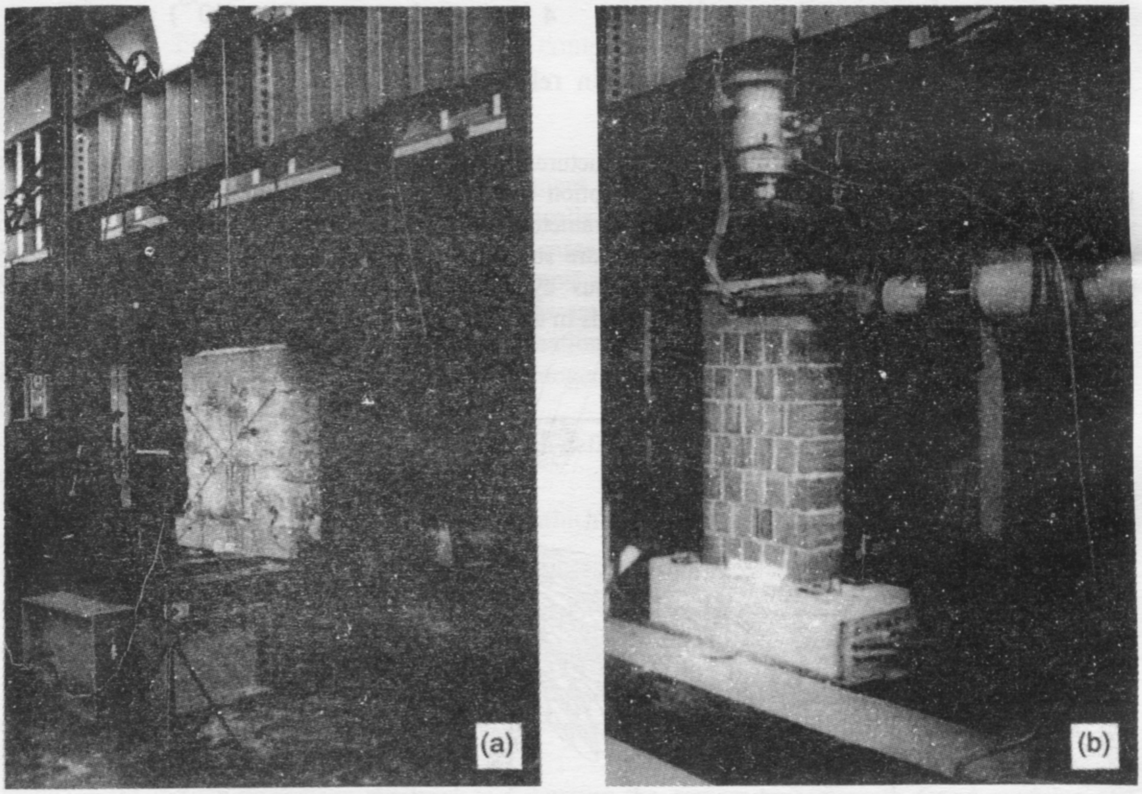

Fig. 4 Seismic resistance tests of masonry walls: (a) fixed ended wall (b) vertical cantilever wall

2. Lateral Load Time History

Because of the cyclic character of seismic loads, various cyclic lateral load patterns, applied statically or dynamically, are used to simulate the seismic loads in different laboratories. Not much information exists on the influence of different ways of testing on test results. The influence of frequency of application of cyclic lateral loads on the strength and ductility of plain masonry walls has been already studied more than two decades ago (Williams and Scrivener, 1974; Terčelj et al., 1977). More recently, differences in the observed behavior as a result of different displacement histories and vertical loads have been discussed (Shing et al., 1990). Static and dynamic response of model masonry houses has been also correlated (Paulson and Abrams, 1990).

Due to the non-linearity and non-homogeneity, the behavior of masonry is not perfectly elastic even in the range of small deformations. Although lateral deformation of the wall is kept constant during a given time interval, changes in resistance and crack distribution in time can be observed during the tests in the non-linear range, which indicates the sensitivity of test results to the time history of lateral loads used for the simulation of seismic loads.

The analysis of test results obtained by testing 32 equal reinforced-masonry wall specimens designed to fail in bending has further confirmed the influence of the shape and velocity of application of lateral load on the test results (Tomaževič et al., 1996). The influence of four different lateral load patterns, monotonic and cyclic, static and dynamic, on the behavior of the walls has been compared at two levels of vertical load acting on the walls. Monotonically increasing lateral displacements (testing procedure A - Figure 5(a)), cyclic lateral displacements with amplitudes, step-wise increasing in pre-defined blocks and repeated three times at each amplitude peak (procedure B - Figure 5(b)), cyclic lateral displacements with step-wise increasing displacement amplitudes, repeated three times at each amplitude peak, with decreasing amplitudes between two consecutive blocks (procedure C - Figure 5(c)), and simulated displacement response of a masonry buildings to an earthquake (procedure D - Figure 5(d)) have been used to drive the actuator.

The walls have been tested at two levels of vertical (axial) load. In the case of the low level of vertical load, the axial load ratio (the ratio between the values of the average compressive stress in the horizontal section of the wall due to vertical load and the compressive strength of masonry) was 0.19, whereas in the case of the high level of vertical load, the axial load ratio was 0.39.

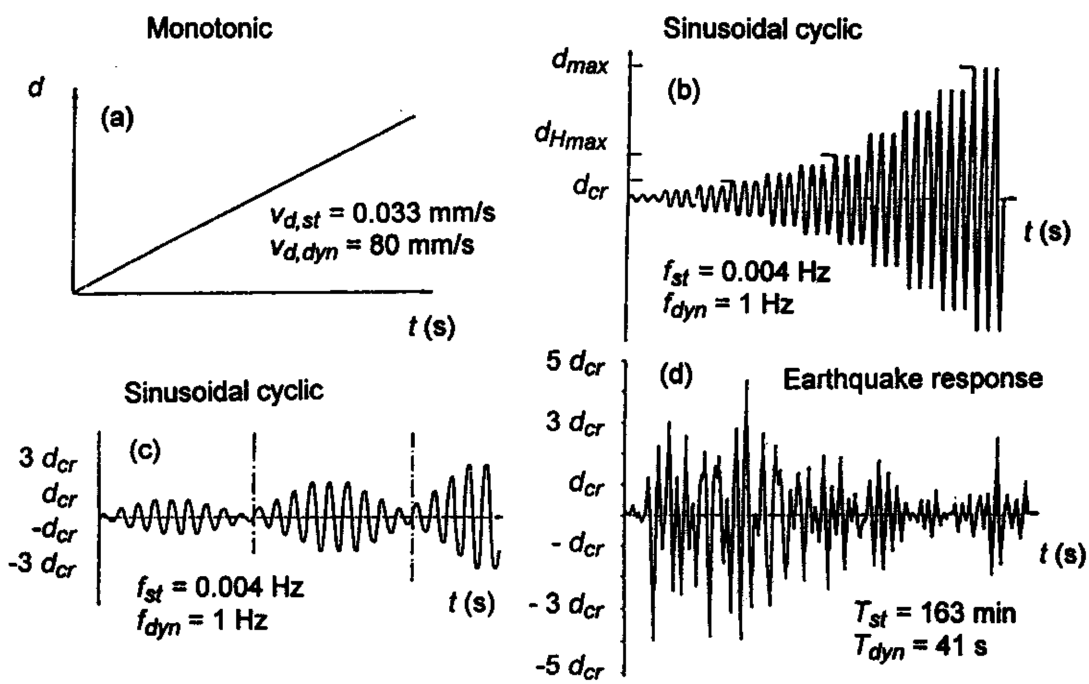

Fig. 5 Lateral displacement time-histories used for the testing of reinforced-masonry walls at ZAG (Tomaževič et al., 1996): (a) A - monotonic (b) B - cyclic, procedure ZAG (c) C - cyclic, modified TCCMAR procedure (d) D - earthquake response

The following main conclusions have been obtained regarding the influence of different loading procedures on the basic parameters of seismic resistance of walls:

Monotonic versus Cyclic Procedure: Higher values of lateral resistance and larger ultimate displacements have been obtained in the case of monotonic than in the case of cyclic loading procedures of any type (Figure 6).

Static versus Dynamic Procedure: Higher values of lateral resistance have been measured in dynamic (fast rate of application of loads) than in static experiments (low rate of application of loads). There was no distinct rule observed regarding lateral deformation and ductility factors. In most cases, similar values of displacements at the attainment of characteristic points of hysteresis envelopes have been measured at both, slow and fast rates of application of loads. Consequently, similar values of ductility factors resulted from both, static and dynamic, experiments (Figure 7).

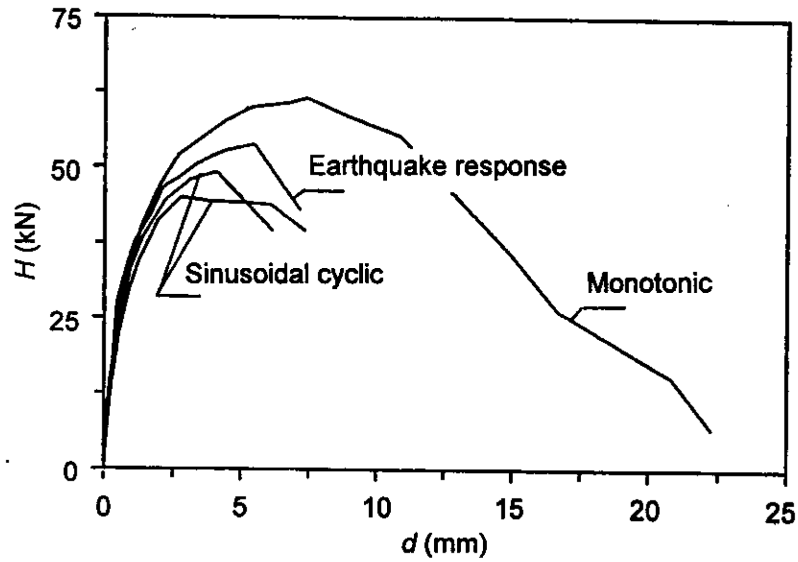

Fig. 6 Comparison of hysteresis envelopes obtained statically at high level of vertical load

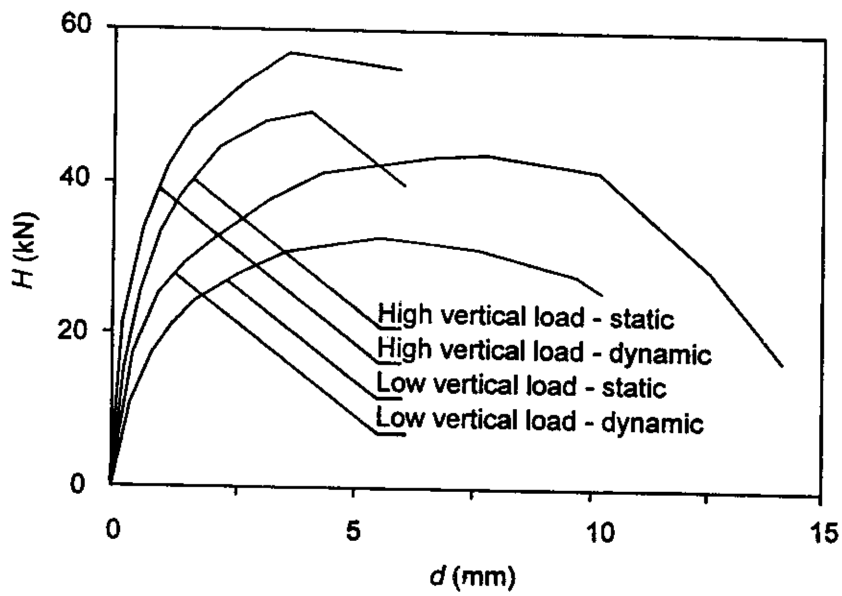

Fig. 7 Comparison of hysteresis envelopes obtained by application of load pattern C

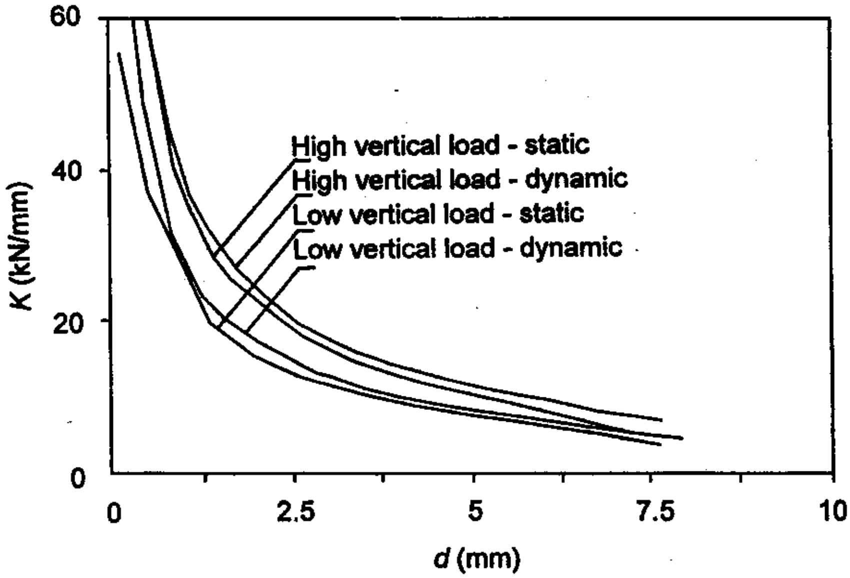

Fig. 8 Relationship between the lateral stiffness and displacements obtained by application of load pattern D

The Level of Vertical Load: The level of vertical load was predominant parameter in all cases. When subjected to higher level of vertical load, lateral resistance of the wall was improved but deformability and ductility decreased at both, static and dynamic, types of loading at all load patterns (Figure 7). The walls subjected to higher level of vertical load were more rigid than the walls tested at low vertical load, and larger stiffness values were determined by dynamic than by static tests (Figure 8). More input energy was needed to cause a given damage status in the case of low than in the case of high level of imposed vertical load. In the case of tests carried out by cyclic loading procedures B and C, the amount of cumulative input energy at the collapse of the wall was more than 100% greater in the case of low than in the case of high level of imposed vertical load. This indicates low energy dissipation capacity and brittle character of the behavior of the walls subjected to high compressive stresses (Figure 9). The failure mechanism and propagation of damage was also affected by the level of the imposed vertical load.

As can be concluded from this study, different results can be obtained by different methods of testing the masonry walls. It is therefore of relevant importance that the testing methods for the determination of parameters of seismic resistance of masonry walls to be used in the design are compatible with the testing methods, on the basis of which the design procedures have been developed.

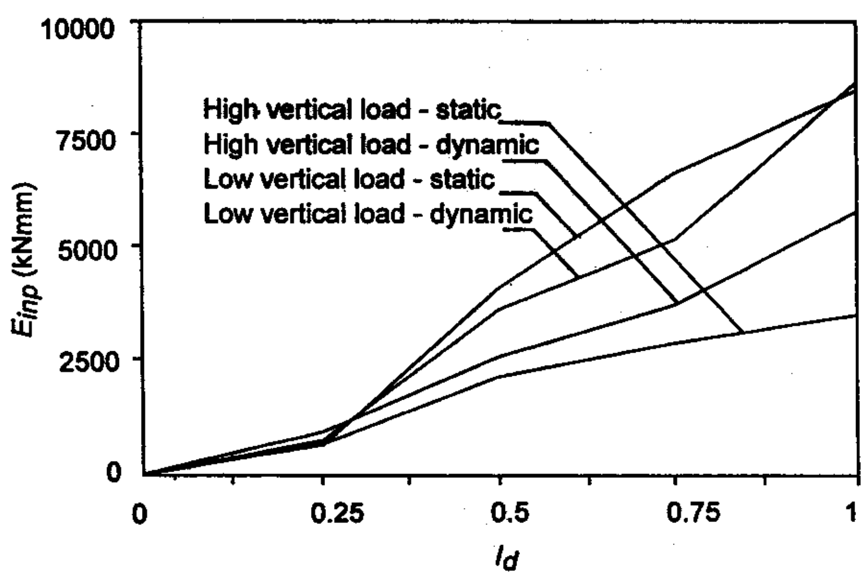

Fig. 9 Relationship between the cumulative actuator work and damage index obtained by application of load pattern B

3. In-Situ Testing

In the case of re-design of existing masonry buildings, the mechanical properties of existing masonry need to be determined. Because of specific properties of masonry materials and the way of construction, it is not easy to fully reproduce the existing masonry walls in the laboratory, although thorough mechanical and chemical analyses of the properties of constituent materials, bricks, stone and especially mortar, would have been previously carried out. Therefore, the values of mechanical characteristics, needed for seismic resistance evaluation, should be determined by either laboratory testing of specimens, cut from the existing buildings, or by testing the masonry walls in-situ.

In the case of the in-situ test, the specimen is separated from the surrounding masonry at an appropriate place by vertically cutting the wall at both sides by means of a saw. After cutting, a system of steel rods and supporting beams, with dimensions adjusted to the actual situation in the building, is installed to transfer the lateral force from hydraulic jack to the specimen. In order to prevent the occurrence of additional damage in the supporting, reaction part of the wall, attention should be paid that hydraulic jack is laterally supported by a strong enough portion of the wall. In vertical direction, the surrounding part of the floor structure is supported with wooden posts or otherwise, in order to prevent the accidental collapse of the floor in the case of possible collapse of the tested specimen.

The specimen is then instrumented with displacement- and strain-meters and subjected to lateral load, simulating the effect of seismic action. Hydraulic actuator, connected to the wall with a system of steel rods and supporting beams, is used to impose lateral displacements, so that the specimens can be tested in the non-linear range. The displacements are gradually increased, with unloading of the specimen at each step, until the resistance deteriorates and heavy damage develops in the walls, just before collapse. Typical arrangement of test and typical lateral load - rotation relationships obtained by testing an existing and strengthened stone-masonry wall are shown in Figures 10 and 11, respectively (Tomaževič et al., 2000).

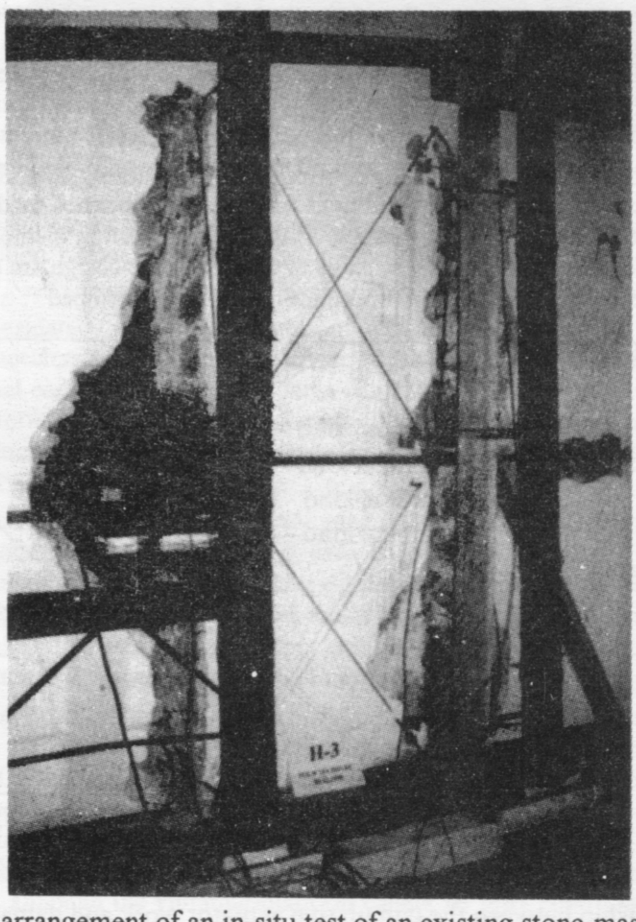

Fig. 10 Typical arrangement of an in-situ test of an existing stone-masonry wall

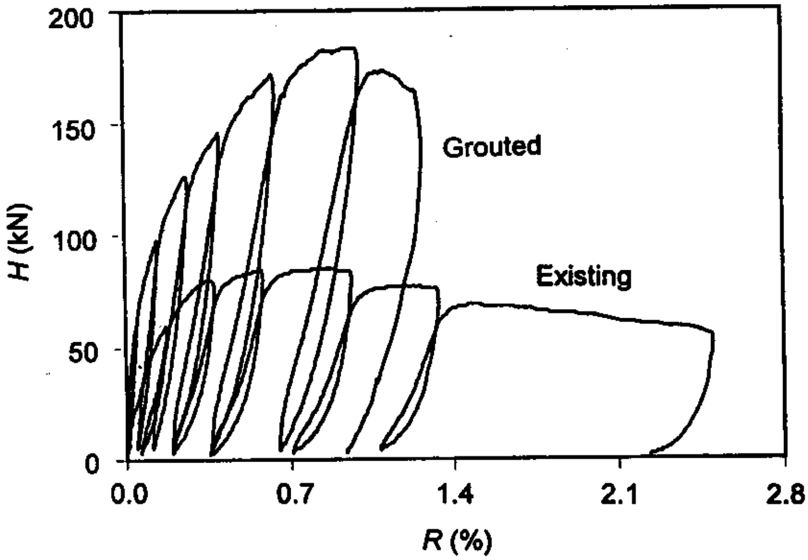

Fig. 11 Typical lateral load - rotation relationships obtained by in-situ test of existing and strengthened stone-masonry wall

SHAKING-TABLE TESTS OF SMALL-SCALE MASONRY BUILDING MODELS

Although basic information concerning the seismic response of masonry walls can be obtained by cyclic testing of masonry walls, complexity and variety of forms of masonry construction systems require additional experimental research in seismic behaviour of complete structural systems. In addition to cyclic tests of masonry walls, earthquake simulator tests should be carried out, where the behaviour of models of buildings or even prototype buildings is studied under simulated earthquake loading conditions.

The development of advanced technologies has made possible the installation of large, multi-degree of freedom shaking-tables which are capable of driving large masses of prototype-sized structures with a high degree of accuracy of reproduction of the recorded or artificial seismic ground motion. However, these testing facilities are rare. Because of the high costs of installation and operation of sophisticated testing facilities, high costs of construction of prototype buildings, and, consequently, high costs of experiments, physical models of structures are still tested on simple earthquake simulators in many laboratories.

Generally, only the overall behavior of the structural system and its global failure mechanism can be determined by testing the small-scale masonry building models, and not the behavior of structural elements and details. When reducing the physical dimensions of the model, the effects of many parameters, such as stress and strain gradients, bond between reinforcement and mortar (or grout), adhesion between mortar and masonry units, etc., on the overall behavior of the structure, change. In most cases, the possibility of modeling the influence of these parameters on the structural behavior to an acceptable degree of accuracy limits the reduction of the size of the masonry building models.

If the behavior of model-sized wallets is similar to the behavior of prototype-sized walls, it can be expected that the global seismic behavior of the building will be also accurately simulated by testing the model on the shaking-table, although not every structural detail of the structure is precisely modeled.

1. Physical Modelling of Masonry Structures

If the seismic behaviour of masonry buildings is studied by testing their models on earthquake simulators, the similitude between the phenomena observed on the buildings subjected to earthquakes and the models subjected to simulated ground motion should be considered as the most important measure of the accuracy of testing procedures. Namely, damage patterns and failure mechanisms obtained during the model tests should be similar to those observed on the prototype buildings after earthquakes. If the failure mechanism of the structural element is accurately simulated and the boundary conditions and loads which acted on the element during the experiment are known, reliable data for the quantification of parameters used in the analytical evaluation of the dynamic response of the tested masonry structure can be obtained. Similitude in dynamic behaviour requires similar distribution of masses and stiffnesses along the height of the prototype and model. Similitude in failure mechanism, however, requires similar working stress level, i.e. working stress/compressive strength ratio in the load-bearing and structural walls of the prototype and model masonry building.

2. Modelling Techniques and Model Materials

If a general quantity q_M has been measured on the model, the following relationship applies for the quantity q_P which refers to the prototype (Langhaar, 1951):

$$q_P = q_M S_q \tag{1}$$

where S_q is a scale factor.

The relationships between the model and prototype quantities strongly depend on the materials used for the construction of the model. In the case of the complete models, model materials are used which have their stress-strain diagram scaled with the geometric scale in the direction of stresses $(S_\sigma = S_L)$, and are the same as prototype materials in the direction of strains $(S_\varepsilon = 1)$. These model materials should also have the same specific weight $(S_\gamma = 1)$, Poisson ratio $(S_\mu = 1)$, and damping $(S_\nu = 1)$ as the prototype ones. In the case of the simple models, however, prototype materials are used for the construction of the models.

Table 1: Scale Factors for the Cases of Complete and Simple Models

Quantity	Equation	Complete model	Simple model
Length (L)	$S_L = L_P / L_M$	S_L	S_L
Strain (ε)	$S_\varepsilon = \varepsilon_P / \varepsilon_M$	1	1
Strength (f)	$S_f = f_P / f_M$	S_L	1
Stress (σ)	$S_\sigma = f_P / f_M$	S_L	1
Young's modulus (E)	$S_E = S_\sigma / S_\varepsilon$	S_L	1
Specific weight (γ)	$S_\gamma = \gamma_P / \gamma_M$	1	1
Force (F)	$S_F = S_L^2 S_f$	S_L^3	S_L^2
Time (t)	$S_t = S_L \sqrt{S_\gamma S_\varepsilon / S_f}$	$\sqrt{S_L}$	S_L
Frequency (ω)	$S_\omega = 1 / S_L$	$1/\sqrt{S_L}$	$1/S_L$
Displacement (d)	$S_d = S_L S_\varepsilon$	S_L	S_L
Velocity (v)	$S_v = S_\varepsilon \sqrt{S_f / S_\gamma}$	$\sqrt{S_L}$	1
Acceleration (a)	$S_a = S_f / S_L S_\gamma$	1	$1/S_L$

The theoretically obtained scale factors which refer to the characteristic physical quantities and determine the dynamic behaviour of structures, are given in Table 1. In this table, the general equations as well as the resulting scale factors for the cases of both, complete and simple, models are given.

The requirements for similitude in dynamic behaviour and failure mechanism are automatically fulfilled in the case of the complete models. However, technological difficulties in manufacturing suitable masonry model materials sometimes limit the exact application of the laws of the complete model similitude. Consequently, scale factors as given in Table 1 for complete models, should be modified. These requirements are also not met automatically in the case where prototype materials are used. In such a case, compensations and adjustments are usually needed. Whereas the similitude in dynamic behaviour is sometimes not extremely important, care should be taken to fulfil the similitude in failure mechanism. Namely, as many past and recent investigations have shown (Tomaževič and Turnšek, 1980; Mann et al., 1988), the failure mechanism of masonry walls is strongly dependent on the working stress/compressive strength ratio (Figure 12).

Table 2: Influence of Added Mass on the First Natural Frequency of Vibration of the Model

Frequency (Hz)	Prototype P	Model with added mass M_a	Model with added mass M_b	Prototype/model (should be: $S_\Omega = 1/5 = 0.20$)	
				P/M_a	P/M_b
Measured	-	13.81	-	-	-
Calculated	2.64	13.43	7.47	0.20	0.35

Index a: mass is added to meet the requirements of similarity of mass distribution

Index b: mass is added to attain the required level of working stresses in the walls

In the case of the complete model, the requirements for similitude of both, mass distribution and failure mechanism, are fulfilled by adding masses which simulate the dead and live loads of floors (concrete blocks, lead bricks or steel ingots). In the case of the simple models, however, by fulfilling the requirement for similitude of mass distribution, the level of working stresses in the load-bearing walls does not attain the level required for the similitude of failure mechanism. If the stresses would be increased by additional weight, wrong conclusions as regards the dynamic behavior of the prototype would be obtained. As can be seen in Table 2, where the first natural frequency of such a model (hypothetical case) is calculated, increasing the stresses in the walls by adding masses to the floors would affect the similarity in distribution of masses along the height of the building and, hence, would significantly modify the dynamic behavior of the tested model.

Therefore, the stresses in the walls should be increased without affecting the similitude in mass distribution. For this purpose, the load-bearing walls are usually prestressed to a desired level with steel ropes, fixed to the top slab and anchored into the foundation of the model. Soft springs at the top end of the ropes are used to keep the prestressing forces virtually constant despite the horizontal and vertical motion of the top of the model during the shaking tests. Tests and calculations showed that the prestressing of the walls with flexible ropes does not significantly change either the dynamic behaviour of the models or the base shear developed during the shaking tests (Tomaževič and Velechovsky, 1992).

Since masonry is inelastic, non-homogeneous and anisotropic material, it is generally not easy to develop and produce model masonry materials suitable for the construction of small-scale models, especially if reinforced-masonry is modelled. Usually, materials are prepared on the basis of experience by using trial-and-error procedures. Since the mechanical properties of the model masonry can be determined only by testing the correspondingly sized model walls, the development of adequate model masonry materials is a time consuming procedure (Tomaževič and Velechovsky, 1992). Namely, in order to evaluate the results of model shaking-table tests, the mechanical characteristics of model masonry should be known. Prior to shaking-table model tests, scaled masonry wallets are tested in specially designed testing facilities, and the results of tests are correlated with the results of tests of prototype-sized walls. Since the seismic behaviour is concerned, mechanical properties obtained by testing the wallets by means of cyclically acting loads, such as tensile strength, ductility and energy dissipation capacity, are correlated in addition to the compressive strength values (Figure 12).

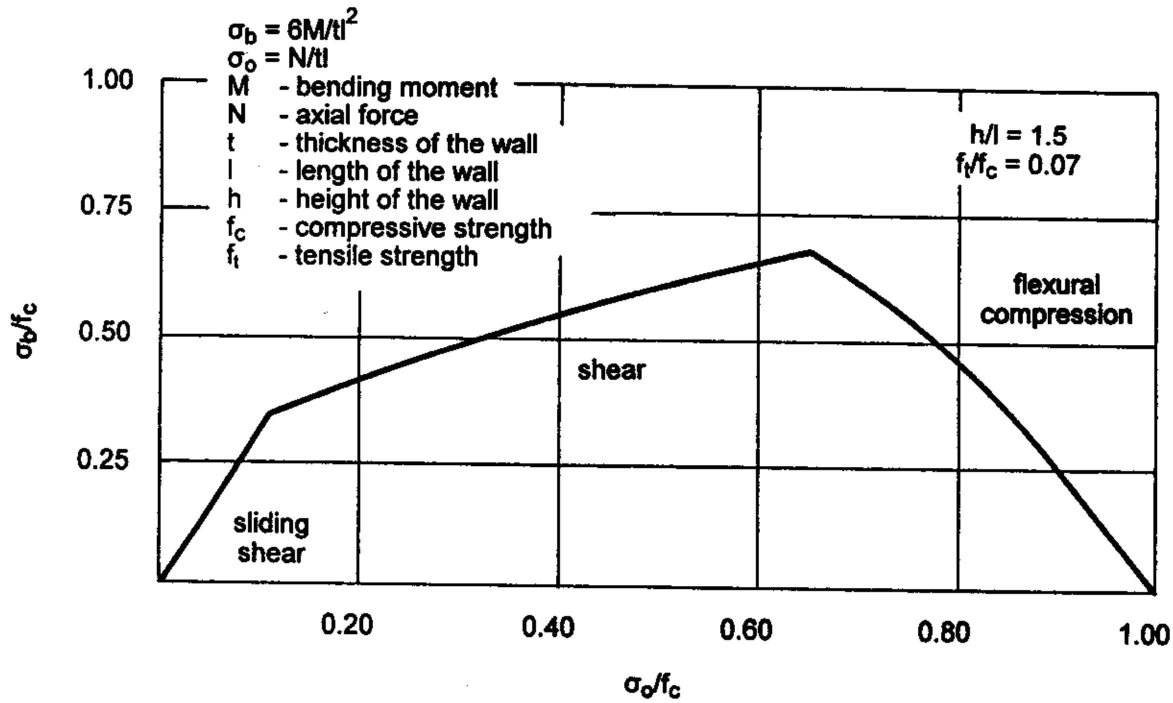

Fig. 12 Dependence of failure modes of masonry walls on working stress/compressive strength ratio after (Tomazevič and Türnšek, 1980; Mann et al., 1988)

At ZAG, a mix of pulverised fuel ash, perlite, fire-clay, corundum dust, and kalven (sodium tripolyphosphate), hand-pressed in a special form, and burned in a kiln, has been used for manufacturing the model blocks for the construction of complete masonry building model at 1:7 scale (Tomaževič 1987). As the production of burned model bricks is time consuming and expensive, a special mortar, composed of crushed brick aggregate, lime, cement and water, has been used in other cases (Tomaževic et al., 1996; Tomaževič and Klemenc, 1997). Compressive strength of the model blocks has been scaled by adequately adjusting the composition of mortar mix. The use of crushed brick aggregate ensured that the specific weight of model blocks was practically the same as that of the prototype. The required size and shape of the blocks has been obtained by casting the mortar into an adequately designed steel form.

Although no special materials have been developed for the construction of the stone-masonry models, the strength of the model stone-masonry, modelled by using natural stone, cut into the correspondingly sized pieces, and low-strength lime mortar, has been reduced so that the models at 1:4 scale have been tested as complete (Figure 13).

In the case where simple models are tested, the prototype-sized bricks or hollow blocks can be simply cut into the correspondingly sized model blocks. In order to model the reinforcement, either aluminium wire or fully annealed wire can be used in the case of both, complete or simple, models.

3. Earthquake Simulator

The idea of using a simple, multi-purpose testing equipment for the simulation of earthquake ground motion is based on the following considerations.

Although the real earthquake ground motion is three-dimensional, vertical components of the ground motion do not significantly affect the seismic behaviour of regular structures, such as masonry buildings. Also, in the case of seismic resistance verification of regular buildings, the structure is subjected to design seismic loads acting in each of the principal directions separately. Therefore, many important data regarding the seismic behaviour of the structure can be obtained by subjecting the tested model to simulated seismic excitation, acting in one of the two principal directions, or askew to one of them.

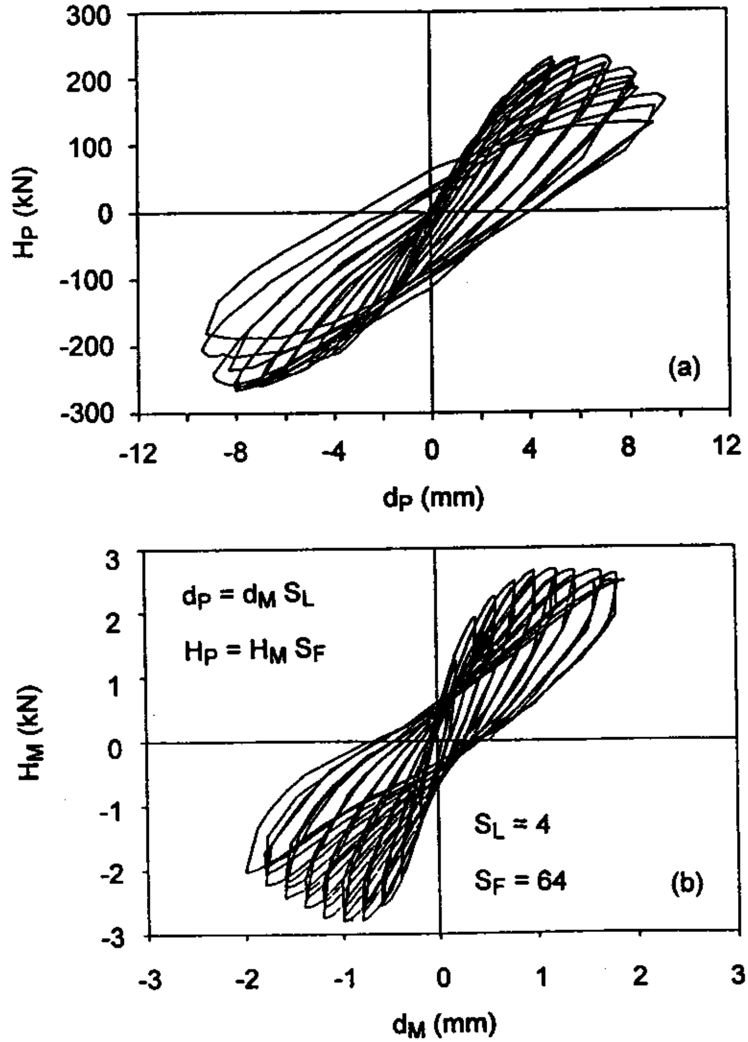

Fig. 13 Correlation between the hysteresis loops obtained by testing (a) the prototype and (b) the 1:4 complete model of a stone-masonry wall (Tomaževič and Velechovsky, 1992)

The earthquake ground motion is a stochastic phenomenon, the characteristics of which depend on the source mechanism and on local soil conditions. However, as the deterministic, dynamic phenomenon, the earthquake will never again occur in the same form. Hence, it is not necessary to test the structures by subjecting them to simulated ground motion which is exactly the same as an actual earthquake record. Reliable results as regards the seismic behaviour of structures can be also obtained by carrying out tests with simple earthquake simulators which are capable of reproducing, in a statistical sense, the characteristics of the real earthquake motion in time and frequency domains.

The earthquake simulator at ZAG consists of two main parts: a horizontally and vertically rail-guided, roller-supported steel platform, onto which the foundation slab of the model is fixed by means of steel bolts, and a two-way acting, displacement-programmable actuator, connected to the platform (Figure 14). A computer is used to control the actuator.

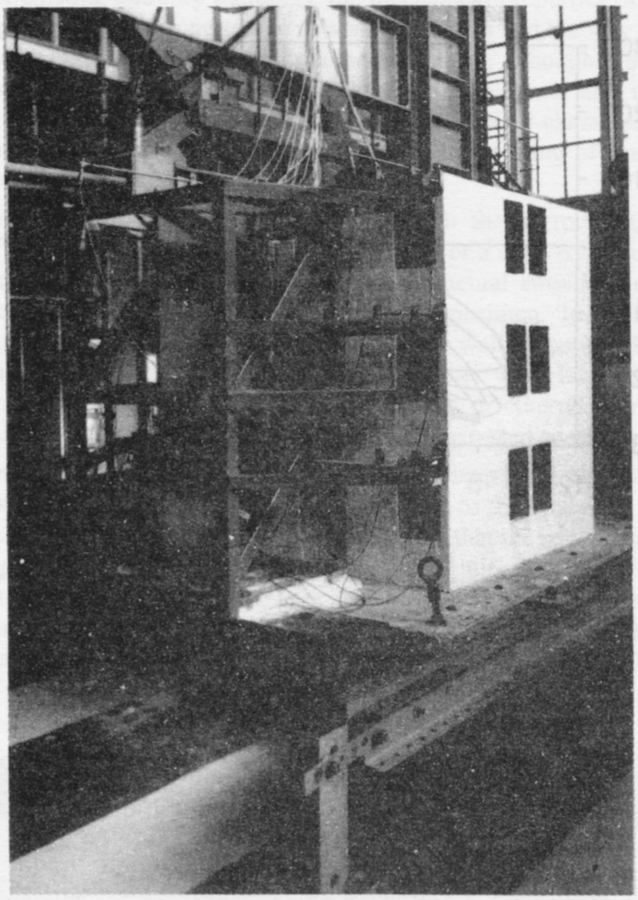

Fig. 14 Shaking-table test of a confined masonry building model at ZAG

In order to determine the demands for the actuator which is used to drive the shaking-table, the peak values of a strong motion record, characteristic for the region, and scaled according to two geometric scales, $S_L = 3$ and $S_L = 5$, respectively, have been calculated. The cases of both, complete and simple, models have been considered. A typical example of correlation between the input accelerogram and scaled shaking-table accelerations is shown in Figure 15. As can be seen, the actuator is capable of reproducing the original earthquake record to a large degree of accuracy, however, with a limited driven mass fixed to the platform. In the case of testing of simple models built of prototype materials, however, the demand for reproducing high accelerations exceeds the capacity of the actuator at high frequencies of excitation (higher than 50 Hz).

In order to estimate the reliability of functioning of the simulator, the correlation between the different parameters of the input accelerogram used to control the actuator motion, and the actual acceleration time-history measured on the vibrating-platform, has been studied on a series of experiments. Good correlation as regards the peak acceleration values has been obtained if the actuator was simulating the modelled earthquake. However, the lack of power of hydraulic pump resulted into the unsatisfactory behaviour of the actuator at the extreme intensity of motion.

The correlation of other parameters, which define the seismic motion, such as Arias intensity, response spectra, and frequency content also indicated acceptable level of similitude (Tomaževič and Velechovsky, 1992). On the basis of these analyses, it can be concluded that the actuator is capable of reproducing, with reasonable accuracy, the intensity and frequency content of the modelled input seismic motion. The correlation between the modelled input and the actual output shaking-table motion is acceptable even at high intensity of shaking, which exceeds the intensity of the modelled earthquake by 2- to 3-times. Moreover, although the vibrating-platform cannot be fully controlled at extreme intensity of shaking, the simulated motion will still maintain the main characteristics of the input earthquake.

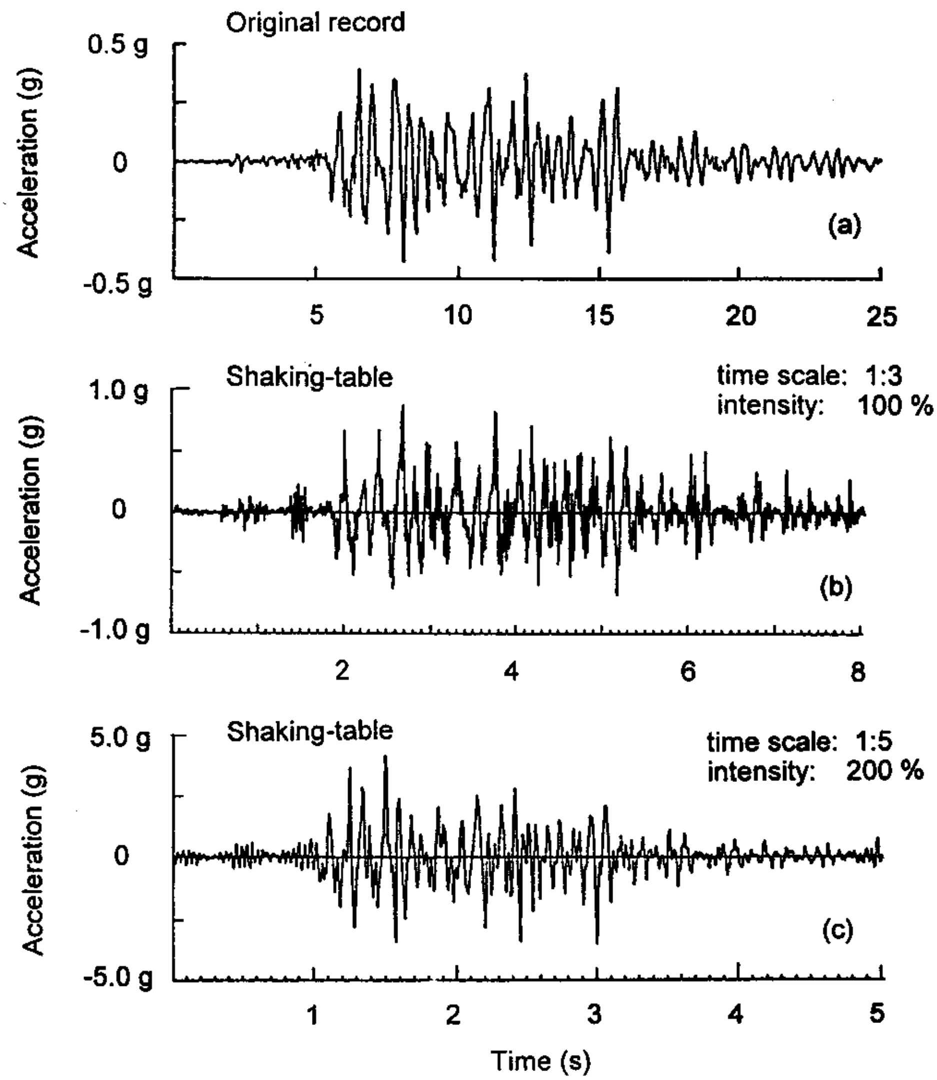

Fig. 15 (a) Input accelerogram and typical shaking-table accelerations scaled at (b) 1:3 and (c) 1:5 scale (Tomaževič and Velechovsky, 1992)

CONCLUSIONS

Some aspects of experimental testing of masonry walls and models of masonry buildings have been discussed. It has been shown that information regarding the strength characteristics of masonry materials can be obtained by monotonic tests, whereas cyclic tests are needed to obtain information regarding the deformability characteristics as well as ductility and energy dissipation capacity of masonry walls.

It has been also shown that the level of imposed vertical load as well as the shape and velocity of application of lateral displacements influence the obtained values of parameters of seismic resistance of masonry walls. It is therefore of relevant importance that testing methods for the determination of these parameters, which are used in the analysis and design, are compatible with the testing methods, on the basis of which the mathematical models and design procedures have been developed.

As the correlation of experimental results with the observed effects of earthquakes on masonry buildings indicates, reliable information as regards the global seismic behaviour and failure mechanism can be obtained by testing small-scale models of buildings on simple earthquake simulators, although neither the physical models nor the seismic ground motion are modelled in great detail. Either special model materials for complete or prototype materials for simple models can be used for the construction of the models. However, considering the technological possibilities of manufacturing complete model materials, the scale of the models should be limited to 1:5. Whereas no adjustment is needed if a complete model is tested, compensation to meet the requirements of dynamic similitude and failure mechanism is needed in the case of the simple models made of prototype materials.

Practical limitations of modelling techniques and the simulation of earthquake ground motion, however, require that additional experiments to determine the characteristics of model materials and model masonry walls as well as the simulated earthquake ground motion be carried out in order to evaluate the effects of these limitations. Specifically, the limitations in the capacity of the actuator (maximum driven mass) and resonant frequency of the testing facility are of relevant importance when deciding upon the size and structural configuration of the models. Also, the influence of model - shaking-table interaction on controlling the earthquake simulator motion should be taken into account in each particular case.

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