Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.1

TESTING FOR THE ASSESSMENT OF EARTHQUAKE RESISTANCE OF HERITAGE MASONRY BUILDINGS:

nondestructive versus destructive, laboratory versus in-situ testing

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Abstract

Some considerations, regarding testing methods, aimed at providing information needed to assess earthquake resistance of heritage masonry buildings, are presented. Various testing methods are available, including non-destructive, semi-destructive, and destructive testing, both in-situ and in the laboratory. Because of specific properties of masonry, non-destructive tests on the basis of propagation of sonic and seismic waves, as well as radar scanning cannot directly provide values of mechanical properties of masonry. They are good for discovering irregularities, such as voids in the masonry, filling the openings in masonry walls and changes in masonry structure. Semi-destructive tests, like shove and flat jack tests provide information regarding the existing stress state in the structural elements as well as shear and compressive strength of masonry. Scratch and impact hammer tests provide information regarding the strength of mortar and units. However, careful calibration of test results, which requires destructive testing in each particular case, is needed to obtain reliable values.

Additional specific testing of structural components and assemblages, as well as complete structures, is needed to assess the values of parameters which determine the seismic behavior, such as displacement and energy dissipation capacity, as well as strength and stiffness degradation and deterioration when subjected to cyclic lateral loads. To obtain relevant information, testing methods which simulate actual seismic conditions, should be used. Since it is not easy to reliably reproduce existing masonry in the laboratory, in-situ tests are preferred to laboratory testing of laboratory prepared specimens. Ultimately, real earthquakes represent best testing fields. Although "testing by earthquakes" is expensive by all aspects, from human to material loss, information obtained by learning lessons from earthquakes is precious and most valuable, if thoroughly studied and understood. On the basis of such information, observed phenomena can be simulated by testing, and methods and procedures can be developed to prevent consequences of future seismic events, if timely applied.

Keywords: masonry, assessment of earthquake resistance, testing, non-destructive testing, laboratory testing, in-situ testing

1. Introduction

Traditional masonry is typical composite construction material, mainly consisting of masonry units and mortar. Natural raw materials, earth, clay and various types of stone are used for manufacturing the units, whereas mortar is composed of mud, lime and sand, mixed with water in the prescribed proportions, with or without additives, such as cement. Units of various types and shapes are laid in various arrangements, and are expected to act together as a homogeneous structural material when subjected to permanent and temporary actions. Traditionally, masonry was aimed at resisting gravity loads: masonry resists compression, however its capacity to resist tension and shear, caused by seismic forces induced during earthquakes, is rather low.

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Earthquake ground motion is three-dimensional. During earthquakes, dynamic forces are induced, which, in addition to gravity, act on the structures, cyclically changing direction of action. Besides materials, structural layout is responsible for energy dissipation and displacement capacity of resisting structural systems. Earthquake (seismic) resistance is the capability of the structure to resist the expected seismic loads by load-bearing and energy dissipation capacity (ductility). According to contemporary standards and codes, a new structure should be designed to resist the strongest expected earthquake which may - with a given probability - occur in the region during a given return period so that human lives are protected, damage is limited, and structures important for civil protection remain operational. Depending on the category of use, same requiremens should be taken into consideration in the case of existing, heritage buildings. Residential buildings should be upgraded to the same safety level as required in the case of the new construction. However, reduction of design seismic loads is sometimes permitted because of costs and feasibility of application of strengthening measures. In the case of monumental buildings, each building represents a specific case. Strengthening is a compromise between technical demands and preservation requirements.

In the case of the new construction, structural layout and properties of materials are determined by structural design, subjected to revision. Use of materials with certified quality and inspection on the construction site guarantee the compliance with design requirements. In the case of existing buildings, the structural system and materials exist, however, engineering information needed for earthquake resistance evaluation, is missing. Structural system should be identified, the dimensions of the structure and elements measured and the system checked for possible deterioration and damage. Mechanical properties of materials need yet to be determined.

It is not the aim of this contribution to present state-of-the-art of various methods of testing of masonry materials, structural components and structures. Various details of contemporary testing methods of masonry are discussed elsewhere in the relevant publications, too many to be mentioned at this point. The contribution is based on the author's experience obtained at Slovenian National Building and Civil Engineering Institute, (ZAG) in Ljubljana, Slovenia, where experimental research in seismic behavior of masonry structures, new and existing, including heritage buildings, has been one of the major concerns in the past several decades. Although there have been almost unbelievable improvements made in the last decades regarding testing methods, facilities, measuring and data acquisition systems, the basic principles of testing remained.

2. Assessment of Earthquake Resistance

Assessment of earthquake resistance of an existing building is carried out in order to decide whether the building under consideration should be repaired (if damaged after an earthquake) or strengthened to prevent collapse and/or excessive damage when subjected to expected strong seismic event in the future. In the case where the damage observed in the structure after an earthquake is a consequence of expected energy dissipation processes, the structure will be repaired in order to return the building to its original seismic resistance. In the case where the degree of damage is beyond the expected level and/or the assessed resistance level does not meet the requirements for earthquake resistance, the structural system needs to be strengthened. Assessment of earthquake resistance (structural evaluation) of an existing building is the first step in the process of seismic redesign.

By visual examination of the building, the overall qualitative information about the structural system is obtained and possible errors regarding the structural layout, construction and maintenance are identified. The condition of structural and non-structural elements is verified and possible damage documented and categorized. If needed, the dimensions of the building and individual structural and non-structural elements in plan and elevation are measured so that adequate plans can be prepared for subsequent structural evaluation and redesign.

By digging inspection pits, the category of foundation soil and type and condition of foundations are determined. By removing plaster from the walls at characteristic locations in plan and along the height of the building, basic type of the existing masonry can be determined. In addition,

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parts of the buildings which have been eventually rebuilt, reconstructed, or simply added during the building's life-time, can be identified. By drilling or making holes through the walls, information regarding the type of construction and structure of masonry walls can be obtained, which significantly vary from region to region, from urban to rural areas. By opening the floors, the type, dimensions and condition of floor structure can be determined. By opening the walls and floors, information regarding the existence, position and condition of some other elements, relevant for earthquake resistance (such as wall-ties and similar elements) can be obtained. Sometimes, simple devices, such as Schmidt and pendulum rebound hammer as well scratch testing apparatus, are used during visual inspection of the building to obtain basic information regarding compressive strength of masonry units and mortar. Naturally, the instruments should be calibrated before being used on the site.

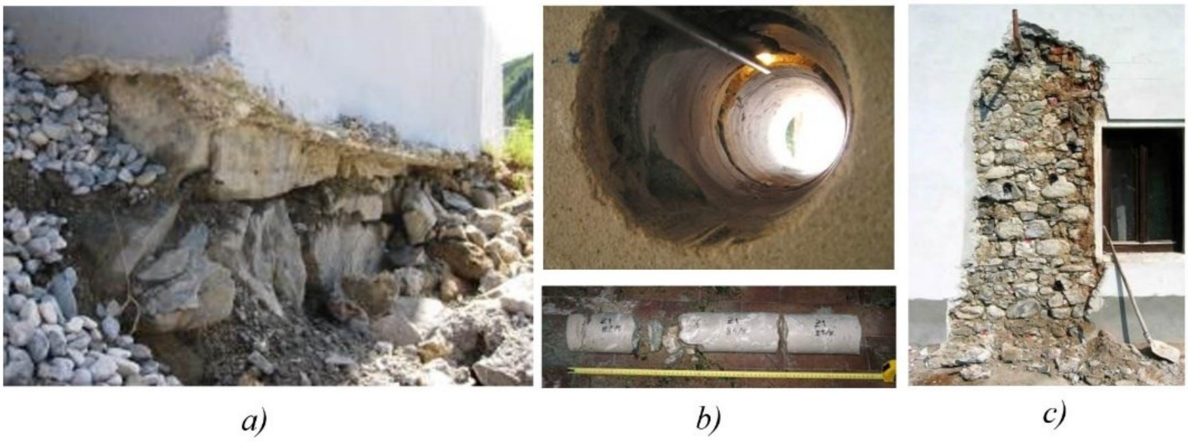

Figure 1. Invasive inspection of foundations and walls. a) Foundation of a small church; b) Drilling in a stone masonry wall; c) Removing plaster to inspect wall typology (Photo: Archive ZAG)

In the case where the original design plans are available, the correctness of information regarding the geometry, position and dimensions of structural elements, as well as type and quality of structural materials, should be verified. In the case where no plans exist, the dimensions of the actual structure should be measured and plans of the existing structure prepared.

3. Testing For the Assessment of Earthquake Resistance

Most important information, needed for the assessment of earthquake resistance, however, represent engineering data, i.e. quantitative information regarding the mechanical characteristics of structural materials and systems. In this regard, testing is indispensable. Although tests are sometimes costly and time consuming, the results of tests represent the only reliable basis for the assessment and subsequent decisions on seismic upgrading. On the basis of a thorough structural diagnosis and assessment of earthquake resistance, technical solutions for improving the resistance of the structure can be proposed and costs of structural interventions, which many times represent critical criterion for final decision regarding strengthening, realistically estimated.

In order to determine mechanical properties of existing masonry, samples of stone, brick and mortar are taken from the wall during inspection, brought to the laboratory and tested. However, since masonry is non-elastic, non-homogeneous and anisotropic material, it is as a rule not possible to determine the mechanical properties of masonry only on the basis of tests of constituent materials. This is possible in the case where the material tests serve as an identification of specific type of masonry with mechanical properties already known. Therefore, testing of masonry walls is usually needed, especially in the case where a large number of buildings of the same typology needs to be rehabilitated. Preferably, such tests are carried out in-situ, hence preserving the actual boundary restraints under which the specimens respond to seismic actions.

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3.1. Non-destructive and Minor-destructive Testing

Non-destructive testing (NDT) procedures, which have been originally developed in medical, mechanical, aerospace and geophysical fields for detecting various discontinuities and errors in homogeneous and elastic materials, have first been used in the field of masonry construction 3-4 decades ago. As testing of mechanical characteristics of existing masonry needs destructive interventions, damaging the building (from in-situ testing to taking samples off the building), the mechanical testing is not accepted from preservation and conservation of historic heritage point of view. Therefore, the idea of modifying NDT methods to be used for obtaining information regarding the mechanical properties of masonry, is logical. Several attempts have been already made (for example [1]) to calibrate the results of NDT methods with the results of "classic" testing to determine basic mechanical properties, such as compressive and shear strength, however with no major practical success.

M.Schuller, one of the pioneers of using NDT and minor-destructive testing (MDT) methods for testing masonry in practice [2, 3], recently wrote: "Recent advances in non-destructive testing technology have led to mainstream use of several methods for evaluating masonry construction. Non-destructive approaches such as rebound hardness, stress wave transmission, impact-echo, surface penetrating radar, tomographic imaging, and infrared thermography are useful for qualitative condition surveys as well as identification of internal features such as voids or areas of distress".

By non-destructive testing (NDT), such as ultrasonic and/or seismic waves propagation measurements, or radar testing, qualitative data regarding the general structure of masonry, defining possibly existing non-uniformities of masonry structures, such as irregularities and voids, as well as existing damage, cracks, etc., can be obtained. Non-destructive tests are helpful in order to identify the general, qualitative condition of the building under consideration. NDT methods are also useful in the case of quality control of applications of seismic strengthening solutions, such as grouting and coating of masonry walls. By using minor-destructive testing (MDT) methods, such as flat jack and shove test, information on compressive and shear strength of masonry, respectively, can be obtained.

3.1.1. Radar Method

The radar method is based on the transmission and reflection of short electromagnetic impulses in the band from 50 MHz to 1,5 GHz. The waves are pulsed by a transducer, whereas a receiver reads the signals reflected off changes in materials, inhomogeneities like voids, or burried objects, like metals (Fig. 2a).

a) *b)* *c)*

Figure 2. Examples of application of typical NDT methods. a) Radar; b) Impact echo; c) Seismic wave velocity measurements (Photo: Archive ZAG, Onsiteformasonry Project [1])

3.1.2. Impact Echo

With impact echo, the impact hammer strikes a masonry surface, generating an acoustic impulse, which propagates into the material and is recorded with a receiving transducer near a striking point. The input energy from the hammer and the reflected compression wave energy from the receiver are

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processed to evaluate structural integrity and locate irregularities, such as voids and delaminations in the wall (Fig. 2b).

3.1.3. Seismic Wave Velocity Measurements

Similar to impact echo method, the hammer strikes the surface of the wall, however, the seismic surface waves, travelling along the wall, are measured. As almost no energy is passing through the air, voids and delaminations of layers in the wall can be detected.

3.1.4. Flat jack testing

The objective of the flat jack test is to obtain the local state of stress in compression of a masonry element that works under vertical stress. The method, originally developed to determine the stress-state in rock masses [4], is based on stress release. Flat jack is a simple device, made of two thin steel plates, shaped as needed and welded together along the borders, with nozzles fixed to the device to pump oil between the plates. Usually two flat jacks are used during the test, placed one above another at a distance of several courses in the slots, made in the mortar bed joints or cut into the masonry. In the case that the stress state in the masonry is analyzed, the general procedure of this test is based on restoring the vertical displacement, which resulted in the part of the wall after cutting the slots. The distance between three or four points fixed across the slot is measured by gages before and after cutting. After placing the flat jacks in the slots, oil is pumped in the jack until the distance between the gage points is restored to the initial situation. In order to obtain the local state of stress, the restoring pressure has to be corrected taking into account the mechanical characteristic of the flat jack, calibrated in the laboratory, and on the relation between the geometry of the slot and the shape of the flat jack [5]. In case that the value of the compressive strength is looked for, the pressure in the jack is increased until the bricks or parts of masonry between the jacks start cracking. Typical example of flat jack test is shown in Fig. 3a [6].

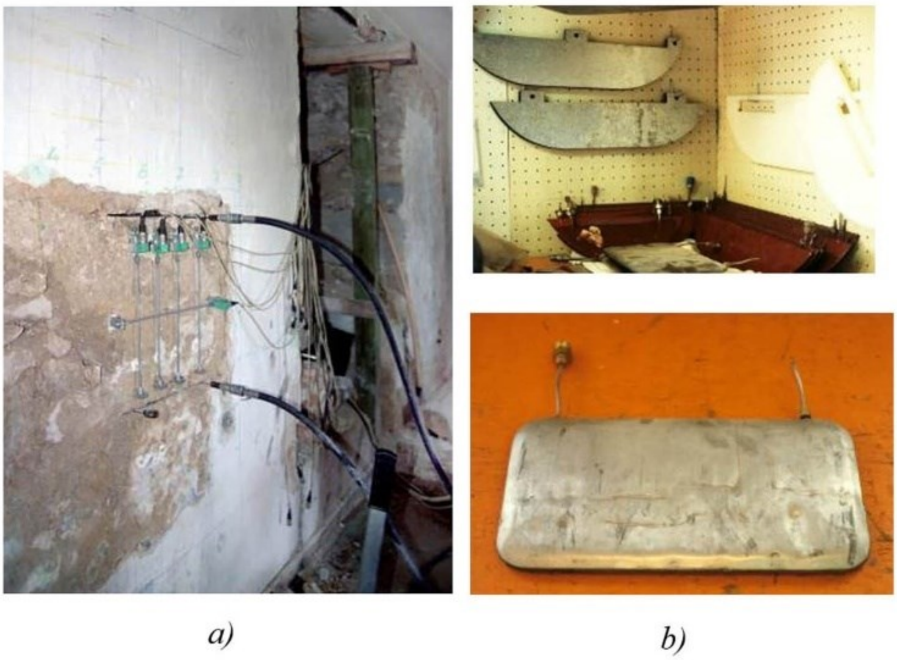

Figure 3. a) Testing compressive strength of a brick masonry wall in Ljubljana [6] and b) Making flat jacks in the laboratory of ANA in Boulder, Co.

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3.1.5. Shove test

Whereas flack jack testing method represents a MDT method to obtain information regarding compressive strength of masonry, shove test is representing an example of MDT method to obtain information regarding the (sliding) shear strength [7].

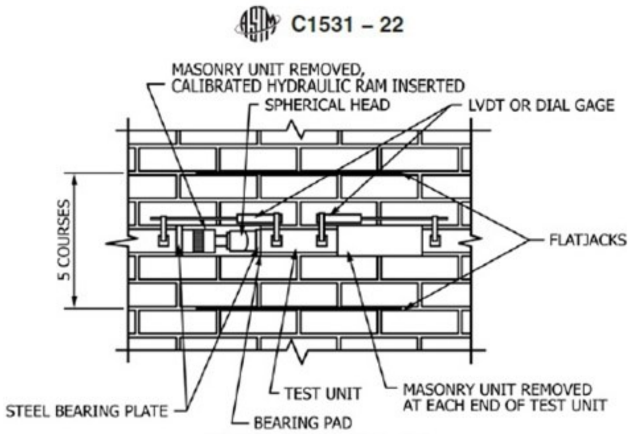

Figure 4. Schematic presentation of a shove test using flat jacks according to [7]

Shove test is applicable to brick masonry, i.e. masonry built of regularly sized units, where sliding shear mechanism (sliding along the bed joints) is one of the possible failure mechanisms. At the selected location, a single masonry unit and a head joint are removed from both opposite ends of the chosen test unit. Using a small hydraulic jack placed in the hole made by removing the unit (or using specially shaped flat jack in the case that only mortar head joint is removed), the test unit is displaced horizontally, relative to the surrounding masonry. The horizontal force required to cause the first movement (sliding) of the test unit provides, as called in the standard, a "measured index of the mortar joint shear strength". To evaluate the test results, actual compressive stress in the wall at the location of shove tests needs to be evaluated. In the case that the test unit is prestressed by means of flat jacks placed above and below the test brick, compressive stresses acting on the test unit are step-wise increased and pushing of the test brick repeated until movement of the brick occurs under increased compression. Hence, the correlation between the compressive stresses and sliding shear strength can be evaluated, similarly as in the case of the triplet test.

3.2. Laboratory Testing of Masonry Walls

Observed failure mechanisms of masonry walls after earthquakes are simulated by testing specimens either in the laboratory or on site. To determine the parameters of seismic resistance, the specimens of the similar size and geometry should be tested at similar boundary restraints as in the actual structural systems, by subjecting them to similar actions as in the case of an actual earthquake. Knowing the geometry of the walls, boundary restraints and loads acting on the walls during testing, equations based on the observed damage patterns and failure mechanisms can be derived and parameters to be used in these equations evaluated on the basis of test results.

The analysis of earthquake damage indicated that sliding shear, shear (diagonal shear), and flexural (rocking) modes represent typical main failure possible mechanisms. However, in the case of the plain stone and brick masonry buildings, including urban and rural heritage buildings, observations of damage after past earthquakes indicated that shear mechanism predominates (Fig. 5a). Typical loads, acting on a masonry pier in seismic situation, are schematically presented in Fig. 5b. Tensile strength (diagonal shear strength) represents the decisive parameter, controlling the shear failure mode. Typical testing methods, by means of which the values of tensile strength of masonry can be determined are schematically presented in Figure 6. Although testing procedures in the case of racking and diagonal compression (diagonal tension) tests are also standardized [10, 11], cyclic shear

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testing method is recommended, because besides tensile strength, additional important information regarding seismic resistance, can be obtained.

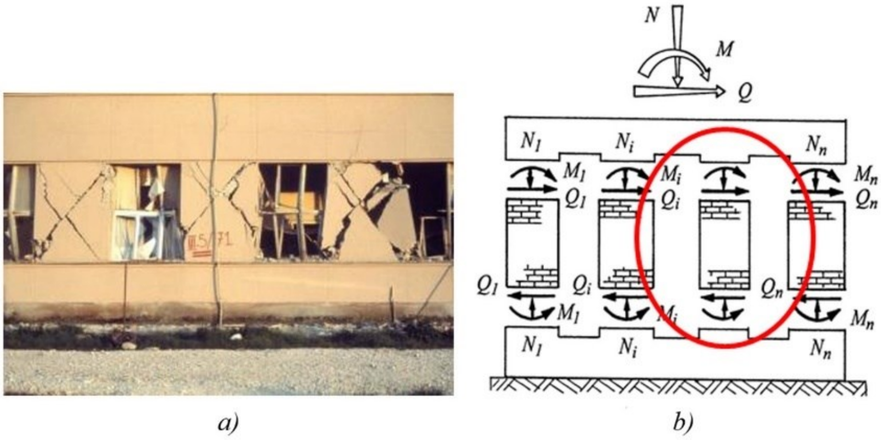

Figure 5. Shear mechanism. a) Failure of brick masonry piers of a school building, Montenegro earthquake, 1979 and b) Forces acting on a masonry pier during earthquake

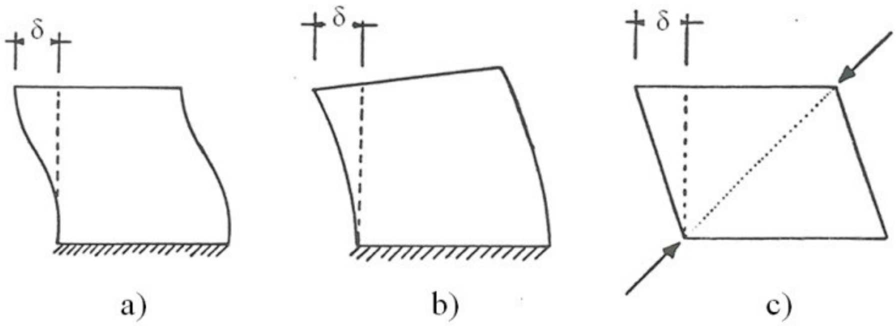

Figure 6. Schematic presentation of different types of tests suitable for evaluation of tensile strength of masonry: a) cyclic test of a fixed-ended wall, b) cyclic or racking test of a cantilever wall, c) diagonal compression test [8]

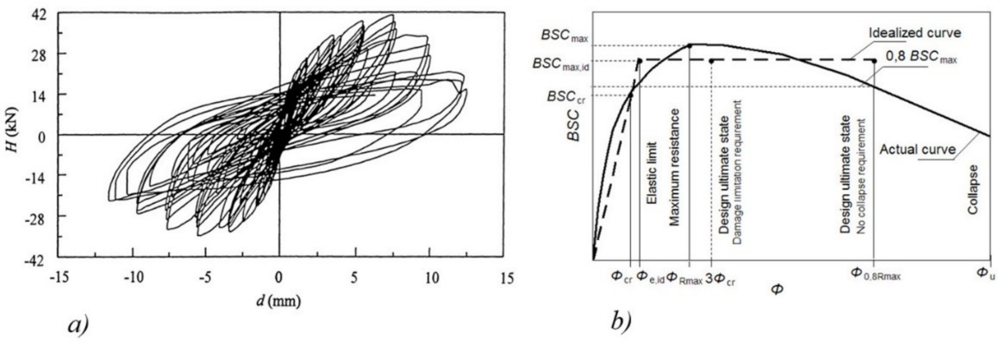

Figure 7. Results of a cyclic shear test. a) Lateral resistance-displacement hysteresis loops
b) Idealization of resistance envelope indicating typical limit states

The comparison of test results, carried out on specimens made of the same type of masonry, has indicated that no statistically significant difference in the values of tensile strength, evaluated by using either of the three testing methods, can be expected [11]. Whereas by diagonal compression tests only the values of the tensile strength can be determined, some information regarding deformability properties of masonry, though of limited value for seismic design, can be obtained by racking tests. Cyclic shear tests are preferred for seismic testing, as they yield almost complete information regarding the seismic behavior of walls, including stiffness and strength degradation as well as displacement and energy dissipation capacity (Figure 7).

Various testing arrangements and various cyclic lateral load patterns (loading protocols), applied statically or dynamically, are used in testing laboratories.

3.2.1. Boundary restraints

Analyzing typical examples of shear failure of URM walls (see Fig. 5a) it can be assumed that the walls are symmetrically fixed at both ends. This assumption has been followed when designing testing arrangements, which keep the upper and lower boundary of the tested walls parallel during the test. Mechanical devices, usually in the form of parallelograms (pantographs), should prevent the rotation of the specimen directly, when placed on the top of the wall, or indirectly by means of a rigid beam, rigidly connected to the parallelogram in the case when placed laterally. Lateral loads from the actuators are transferred to the wall by means of the horizontally moveable part of the parallelogram, placed on the walls. One of the first devices of the kind, designed at ZAG in the late 1960-ties, is shown in Figure 8a.

a) *b)*

Figure 8. Cyclic lateral resistance tests of stone masonry walls. a) Specimen tested as symmetrically fixed b) Specimen tested as vertical cantilever

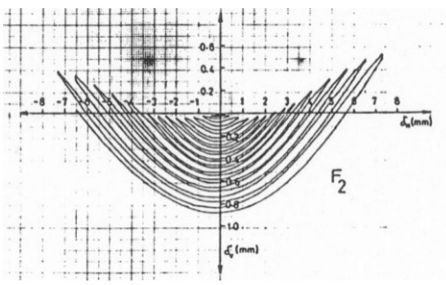

Figure 9. Vertical motion of lower part of the pantograph as a function of lateral displacements, indicating rocking of an URM wall during initial phases of cyclic shear tests [12]

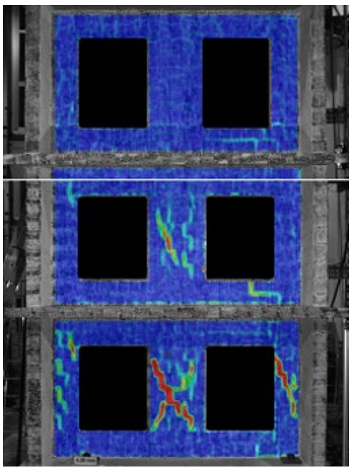

Figure 10. Three story full scale building: digital optical measurements indicate no rocking phenomena of piers [13]

Control measurements of possible vertical motion of the lower beam of the parallelogram indicated that it moves upwards with increased lateral displacement, imposed to the wall during testing (Fig. 9). This indicates that test specimens rock as rigid bodies when subjects to lateral load until cracks and damage occur, what reduces the rigidity of the specimen and, consequently, rocking.

The walls can be also tested as simple vertical cantilevers. In this case, the foundation block on which the specimen is built, is fixed to the testing floor. Lateral load is imposed by means of a programmable hydraulic actuator, fixed to the upper beam placed on the specimen. Vertical load is applied by means of hydraulic jacks. Roller bearings are placed between the steel beam and steel plates on the top of the specimen to allow for the friction-free lateral motion of the wall during cycling (Fig. 8b). However, the analysis of tests results indicated [14] that the arrangement for application the vertical load prevents free rotation of the upper boundary of the walls. In case where the vertical load is applied by two jacks, the restraint is significant, resulting into changes of position of the moment inflection point in the range of 60-80 % of the wall's height. The analysis indicated, that the walls are not tested as vertical cantilevers, fixed at the bottom, but as partly restrained at both ends.

It can be concluded that the walls, supposed to be tested as fixed-ended, are actually tested as symmetrically restrained. On the other hand, the walls, supposed to be tested as vertical cantilevers, are tested as partly restrained at both ends. These facts do not affect the experimentally obtained information regarding the resistance, but make difficult to correctly evaluate the deformability characteristics, as well as all as the mechanism of behavior in the earlier phases of testing.

In the buildings, restraint conditions may change during the earthquake due to progressive damage and consequent changes in rigidities of the walls and horizontal structural elements. However, only exceptionally observed damage patterns indicated rocking behavior of the walls. This has been also confirmed by in-situ (see Chapter 3.3) and large scale laboratory testing, where the phenomena of rocking of walls have not been observed (Fig. 10).

3.2.2. Application of Lateral Loads

In order to be able to study failure mechanisms and non-linear behavior of masonry buildings when subjected to strong earthquakes, displacements, and not forces, are imposed to test specimens during seismic testing. 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. The influence of frequency of application of cyclic lateral loads on the strength and ductility of URM walls has been already studied four decades ago [15, 16]. Differences in the observed behavior as a result of different displacement histories and vertical loads have been discussed. Static and dynamic responses of model masonry houses have been also correlated [17].

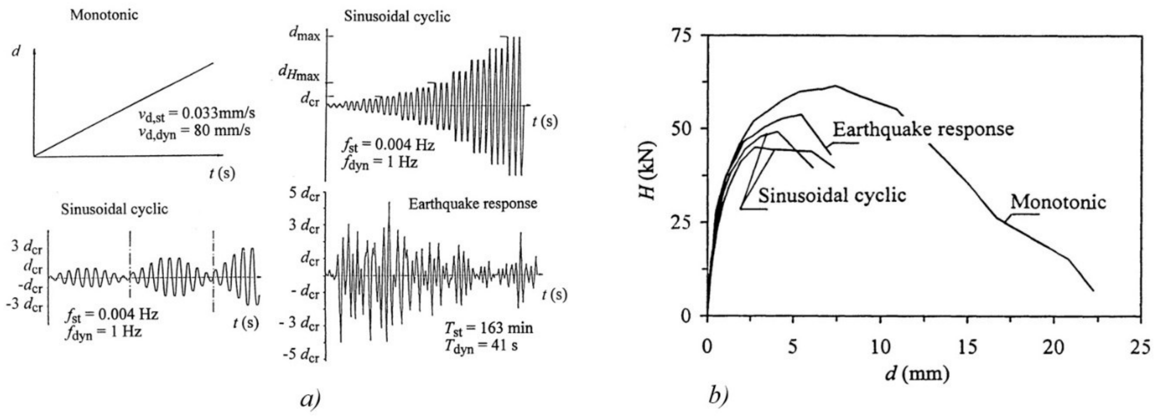

Figure 11. Influence of displacement protocols on test results, a) Test protocols, b) Correlation between resistance envelopes, obtained by application of various displacement protocols [18]

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The analysis of test results obtained by testing 32 equal reinforced-masonry wall specimens at ZAG has further confirmed the influence of shape of the applied displacement time history and velocity of application on test results [18]. The influence of four different lateral load (displacement) 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 (Fig. 11).

It has been found that higher values of lateral resistance and larger ultimate displacements have been measured in the case of monotonic than in the case of cyclic loading procedures of any type. In the case of cyclic testing, higher values of lateral resistance have been obtained dynamically than statically. However, there was no distinct rule observed regarding the differences in displacement capacity. Similar values of ductility factors resulted from both, static and dynamic type of tests.

The level of vertical load was the decisive 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. 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 obtained by dynamic than by static tests. However, displacement and energy dissipation capacity were lower. The failure mechanism and propagation of damage was also affected by the level of the imposed vertical load.

These conclusions are in good agreement with previously mentioned investigations as well as with recent proposals [19]. Since different results can be obtained by different methods of testing, the compatibility between the testing methods, used to obtain the values of input parameters for the assessment of seismic resistance, and testing methods, on the basis of which the numerical models for seismic resistance verification have been developed, is of relevant importance.

3.3.In-situ Testing of Masonry Walls

From the point of view of simulating boundary restraints, testing the wall in situ is far more realistic than testing in the laboratory. The wall is tested as part of the structural system, so there is no need to simulate boundary restraints and gravity loads: the same interaction forces between the surrounding horizontal and vertical elements and the tested specimen will develop during lateral resistance test as in the case of the real seismic situation.

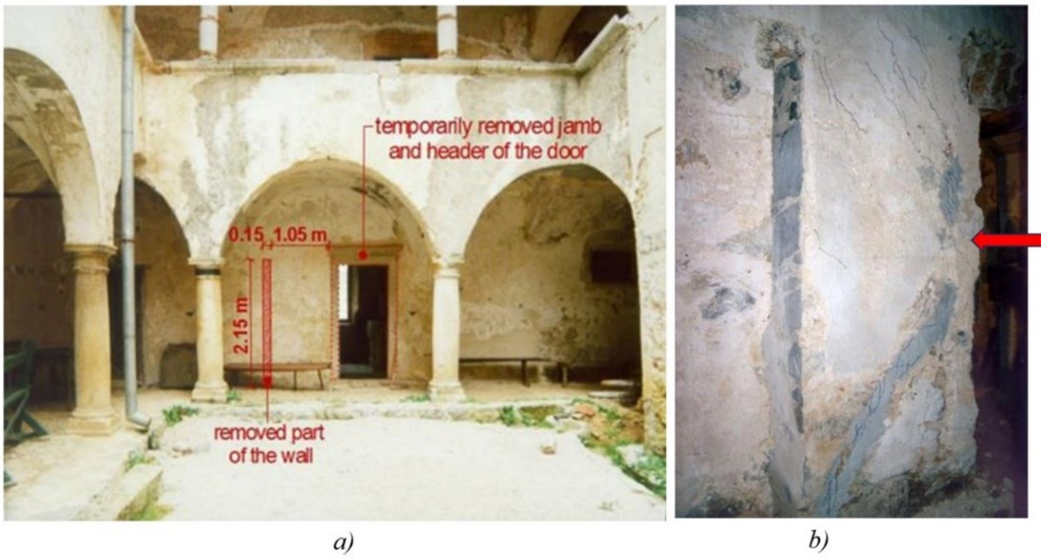

Figure 11. In situ test of a wall in Gracarjev turn Castle. a) Selection of testing location; b) Diagonal cracks in the wall after the end of test. No horizontal cracks at the ends of the wall are visible

The specimen to be tested is separated from the surrounding masonry by vertical cuts at both sides. Horizontal force is induced at the mid-height of the wall by a system of steel rods and

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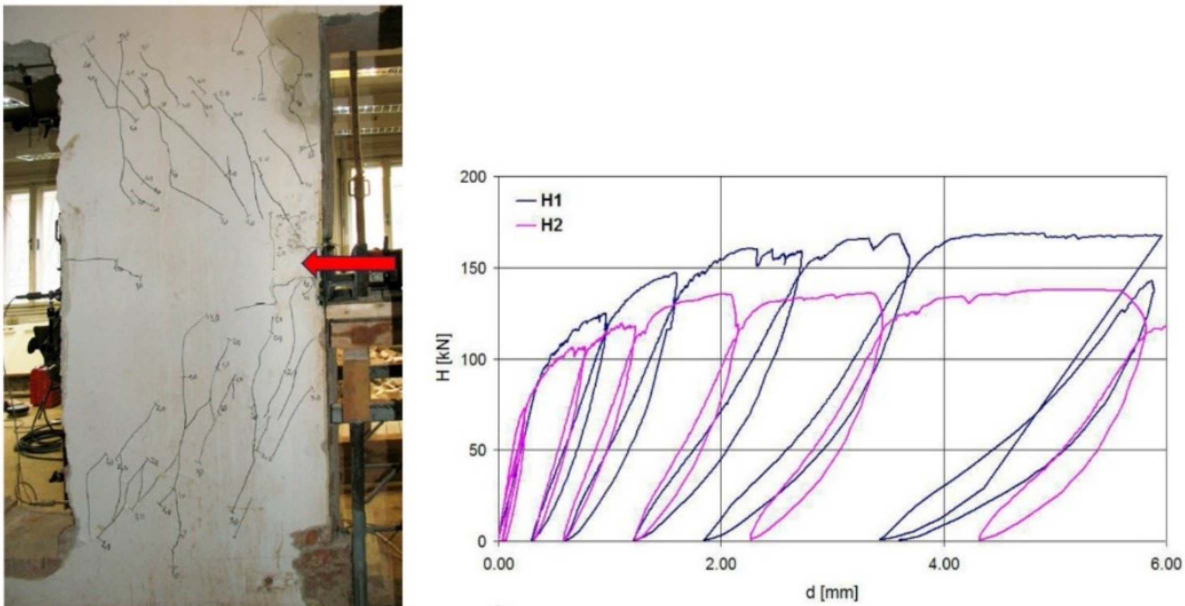
supporting beams, with dimensions adjusted to actual situation in the building. Care should be taken to select appropriate location and size of the tested part of the structure. In order to prevent damage to other parts of the building, hydraulic jack should be supported by a strong enough portion of an adjacent wall. In the 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 sudden collapse of the tested specimen.

Since vernacular masonry is non-homogeneous, it is not easy to reproduce the existing masonry walls in the laboratory, even though existing material is used and very thorough chemical and mechanical analysis of mortar, brick and/or stone may have been carried out. The only reliable method of determining the load-carrying capacity of existing old masonry walls involves the carrying out tests in situ, or cutting out specimens from these walls and test them in the laboratory. However, the method of testing is destructive and will be hardly approved by authorities of conservation and preservations of architectural cultural heritage. If approved, one has to bear in mind that sophisticated laboratory testing equipment cannot be moved to the testing site. Instead of programmable actuators used for cyclic shear tests, simple hydraulic jacks and monotonic cyclic loading test methods (Fig. 12b) are applicable. Therefore, full size specimens are sometimes cut off the building and transported into laboratory. Besides being time consuming, cutting of the specimens, preparation for transport and transport to the laboratory require careful handling.



b)

a)

Figure 12. In situ testing of a brick masonry wall. a) Crack pattern after the end of tests. No horizontal cracks at supports can be seen; b) Lateral load-displacement relationships, obtained by monotonic cyclic testing [6]

3.4. Testing of Dynamic Characteristics of Buildings

In the case where information is needed about dynamic characteristics of the building under consideration, such as natural periods of vibration and damping, special tests are carried out. For this purpose, various methods and techniques are available. By means of dynamic exciters, fixed on the floors, vibrations of the building are induced. In this case, the frequency of rotating eccentric masses is electronically controlled and the response of the structure at different points along the height of the building at each frequency of excitation is measured. By evaluating the resonance curves measured during excitation, the coefficient of equivalent viscous damping can be also determined.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.1

Ambient vibration tests are simpler. In this case, vibrations of the building, induced by seismic microtremors, traffic, wind and other environmental influences are measured with sensitive transducers, placed on the structure at different locations along the height of the structure. The vibrations are measured for sufficiently long time and analyzed. Again, on the basis of the calculated Fourier response spectra, information is obtained about the structure's natural vibration periods and structural damping.

One has to bear in mind, that such information is obtained at small energies of excitation, where the tested structural system behaves more or less elastically. They represent dynamic characteristics of buildings in the initial phases of seismic excitation and cannot be considered as "effective" when assessing the seismic resistance.

4. Testing of Small-scale Models on Simple Earthquake Simulators

To understand seismic behavior of structures, testing of individual components is not enough. Since the basic principles of earthquake resistant design assume that energy is dissipated by means of non-linear response, i.e. damage occurring to the structures when subjected to design level earthquakes, not only linear elastic, but also inelastic response of the system in the non-linear range should be known. The understanding of mechanism of behavior in the non-linear range is needed not only to develop and validate sophisticated numerical models, but also to assess reliable values of many code-required coefficients used in the process of earthquake resistant design. To obtain such information, the observed earthquake damage to buildings should be reproduced by testing the entire structural systems, not only individual structural components, under simulated earthquake loading conditions.

Nowadays, development of high technologies 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 simulation of the spatial, recorded or artificial seismic ground motion. Of course, the response of the tested structure to spatial ground motion, taking into consideration in-plane, out-of-plane and vertical components of seismic action on structural system and components, is close to the actual seismic response. There is no better way to simulate seismic behavior of a structure in the laboratory. Unfortunately, costs of installation, maintenance as well as experiments by using such devices are high. Therefore, structures at reduced scale, i.e. physical models of structures, are still tested on simple earthquake simulators in many laboratories.

There are advantages and disadvantages of model testing. Such tests are cheaper than full scale tests. Testing facilities are simpler and in many cases, hydraulic actuators, used to drive the platform when used as a shaking table, can be dismantled and used for other kinds of testing. The construction of models is cheaper, although many times not simpler than the construction of prototype. Adequate model materials, whose characteristics depend on the modelling scale, should be used (developed), depending on the modelling scale. To develop such materials and verify how the mechanical characteristics of model and prototype materials comply with the similitude laws, takes time. In the case where the prototype is tested, no such problems need to be resolved. Modelling techniques can be adjusted to possibilities which, however, this requires caution when interpreting the test results.

Generally, only the overall behavior of structural system and its global failure mechanism can be determined by testing 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 modelling 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.

The excitation is usually one-directional, which provides better control of the observed mechanisms of structural behavior. However, one has to bear in mind that sometimes seismic actions in other directions (out-of-plane, vertical) influence the observed mechanism.

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.1

Accuracy of simulation of seismic motion represents a technological problem of test control. As the experience shows, it is important that the induced shaking's spectral characteristics are similar to actual characteristics of earthquakes. In case that the actual shaking table motion is accurately recorded, matching the input and output motions is not of relevant importance. Earthquakes with the same dynamic characteristics, duration and acceleration time histories, never occur twice: when analyzing the response of the model, the recorded motion of the shaking table represents the earthquake to be considered as the dynamic input, and not the scaled actual earthquake.

By testing models of buildings on shaking tables, phenomena observed on the buildings during earthquakes are simulated, and physical quantities, which determine the seismic response, are measured in order to analyze the behavior. Obviously, it is the similitude of behavior and failure mechanisms of a real building, subjected to an actual earthquake, and its reduced size replica (model), subjected to simulated earthquake, which is the measure of success and accuracy of the testing procedure. Damage patterns and failure mechanisms obtained during model tests should be similar to those observed on the prototype buildings during earthquakes. If the failure mechanisms of structural elements and the entire building are accurately simulated and the boundary conditions and loads which acted on the elements during the experiment are known, the measured data can be used for reliable prediction of seismic response of the prototype.

4.1. Model materials, models and similitude

The modelling techniques and similitude conditions are discussed elsewhere [20, 21]. Basic relationships between physical quantities measured on the prototype and model are determined on the basis of dimensional analysis [22] and depend on the mechanical properties of materials used for the construction of the model and modelling scale. In the case where elastic behavior if the structure under static loads is studied, the relationships between the prototype and model structures are straightforward. However, if the dynamic behavior in the nonlinear range and failure mechanisms are investigated, model materials and testing techniques should be carefully selected in order to reliable reproduce the behavior of the prototypes.

Although the theoretical requirements for model similitude are sometimes difficult to fulfill, two basic conditions should be fulfilled in order to obtain reliable information:

- the distribution of masses and stiffnesses along the height of the model and prototype should be similar (similitude in dynamic behavior);
- the working stress in masonry walls/compressive strength of masonry ratio in the case of the model and prototype walls should be similar (similitude in failure mechanisms).

If both conditions are fulfilled, the seismic response and failure mechanisms of the model and prototype will be similar. This will make possible the conversion of values of physical quantities, measured on the model, to the prototype in accordance with similitude laws. Whereas the similitude in dynamic behavior is not always of decisive importance, care should be taken to fulfil the similitude in failure mechanism.

Usually, model materials are manufactured on the basis of experience by using trial-and-error procedures. Although the mechanical properties of constituent materials, model masonry units and mortar, are modelled to a required degree of accuracy, the final correlation between the model and prototype masonry is assessed by comparing the results of tests of model and prototype walls at both, compression and cyclic shear loads. Prior to shaking-table model tests, scaled masonry wallets are tested. Since the seismic behavior is concerned, besides mechanical properties of masonry, failure mechanism and damage propagation, as well as displacement and energy dissipation capacity, are also correlated.

4.2. Earthquake simulator and modelling of seismic ground motion

The idea of using simple, single-directional shaking table, driven by multi-purpose hydraulic actuator, to study the seismic behavior of building structures, is based on the following considerations.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.1

Although actual earthquake ground motion is three-dimensional, vertical components of the ground motion do not significantly affect the seismic behavior of regular structures, such as masonry buildings. Also, many important data regarding the seismic behavior of the structure can be obtained by subjecting the tested model to simulated seismic excitation, acting in one of the two principal directions of the building, or askew to one of them. 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. Therefore, the decision regarding the type of the shaking table motion is usually taken by considering the similarity between the response spectra of the acceleration time history, used to drive the shaking table, and the design response spectra, required by the codes (Fig. 14a). In this regard, synthetic accelerograms, calculated on the basis of the design spectra, can be also used. Once the decision is made, accurate simulation of the chosen seismic input does not represent serious problems. Usually, earthquake simulator motion is calibrated by considering the capacity of the actuator, payload (mass of the model and its foundation slab, including mass of the moveable platform), and modelling scale.

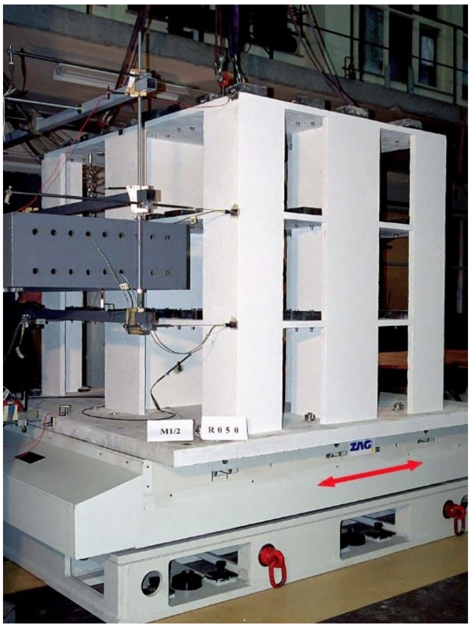


Figure 13: Earthquake simulator at ZAG

For example, earthquake simulator at ZAG (Fig. 13) consists of a rigid foundation steel box, fixed to the r.c. laboratory testing floor, and a moveable, 2.0/3.2 m box-type steel platform, onto which the foundation slab with the model is bolted and which is moved by means of a programmable hydraulic actuator. Depending on the actuator coupled to platform, the simulator is able to accurately drive the payload of up to 5000 kg mass with motion of typical earthquake spectral characteristics, needed when testing models at up to 1:5 scale. Displacement time history, used to drive the actuator, is obtained by double integration of the chosen earthquake accelerogram. Nevertheless, accelerations measured on the shaking table during the tests, match the input acceleration record surprisingly well (Fig. 14b). The calibration measurements have shown that the moveable platform is rigid enough for carrying the bending loads, developed as a result of interaction between the model and platform during the shaking tests.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.1

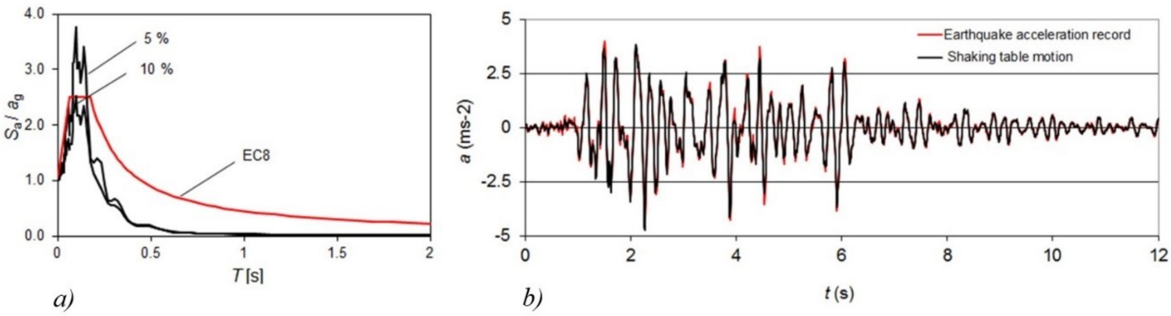


Figure 14. a) Response spectrum of the model earthquake in correlation with EC8 spectrum
b) Typical correlation between the input and output accelerogram, measured on the simulator

4.3. Example: testing the influence of steel ties on the seismic behaviour of stone masonry houses

As an example of usefulness of model testing on simple simulators, the study of effectiveness and mechanism of action of wall ties, which connect the walls at floor levels, prevent disintegration and ensure integrity of structural system when subjected to strong earthquakes, will be briefly presented [23]. A series of models of simple stone masonry houses with wooden floors, with and without wall ties placed at floor levels, as well as with r.c. floors or brick vaults replacing wooden floors, have been tested on the shaking table by subjecting them to a series of simulated ground motions with increased intensity of motion in each subsequent test run. Acceleration time history, recorded during an actual strong earthquake, scaled according to modelling scale, has been used to drive the earthquake simulator. The intensity of motion has been gradually increased up until the collapse of the models. Typical situation of the models with wooden floors, with and without ties at the end of tests is shown in Fig. 15.

Figure 15. Failure mechanisms obtained by shaking table tests of stone masonry models
a) Model without ties; b) Model with wall ties

As can be seen, the upper storey of the model without wall ties disintegrated and collapsed, whereas in the case of the model with wall ties, separation and disintegration of the walls was prevented. The model collapsed because of the shear failure of the load-bearing walls in the first

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.1

storey. Both models resisted the approximately same base shear, however, the model with wall ties resisted repeated seismic action with intensity 50 % stronger than the earthquake which caused the collapse of the model without ties. Information of this kind could have been obtained only by shaking table test.

By measuring strains in the walls ties, mechanism of tie action has been defined and a model for designing the dimensions of ties proposed.

5. Conclusions

Assessment of earthquake resistance of heritage/existing masonry buildings is a complex procedure. By visual inspection, investigations and measurements, the type, geometry and conditions of the building and structural elements are determined. However, destructive, or at least minor destructive tests are indispensable to obtain engineering data. In this regard, existing information obtained on similar buildings of similar typology may reduce the amount of testing provided that similarity in typology and construction materials has been proved by identification testing. Destructive tests are also the only means to validate the efficiency of proposed strengthening methods.

Initial dynamic characteristics of the building's structural system may be defined by forced vibration or ambient vibration techniques. Sometimes, the structure is monitored and short and long-term observations and measurements are performed to collect the relevant information for structural evaluation. On the basis of the obtained data, standard or sophisticated computational models are developed, seismic resistance is verified and, consequently, decision can be made as regards the necessary structural interventions.

NDT methods are helpful in identifying the overall situation of the structure. They represent the best means for quality control of interventions for structural strengthening.

Acknowledgements

The paper is based on the author’s long-time experience obtained by conducting experimental research at Slovenian National Building and Civil Engineering Institute. Additional details can be found in referenced publications and elsewhere.

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