Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Seismic Analysis of Historical Structures Using Passive Control Systems

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ABSTRACT: In this paper, an integrated procedure for the seismic analysis of masonry historical structures, before and after their retrofitting, is proposed. The procedure concerns three aspects, the failure analysis of masonry structures using the finite element method, the implementation of three-dimensional solid elements for the detailed consideration of out-of-plane loadings and the vulnerability evaluation of historical structures using a fragility curves diagram. For each aspect a developed methodology is presented. Their application is used for the evaluation of structural retrofitting using passive control systems and especially dampers. For this purpose, three case studies of existing historical structures are presented: a church with a cistern, a slender minaret and a railway arch bridge. Efficiency and applicability limits of dampers are discussed through the application of the proposed methodologies and conclusions are drawn concerning the intervention method and the analytical evaluation procedures.

1 INTRODUCTION

When an earthquake attacks a masonry structure, failure usually occurs due to its low tensile strength, in contrary with its notable strength in compression. Masonry's inherent characteristics such as its non-homogenous nature as well as the variability of the quality of the construction also affect its seismic vulnerability and render difficult any exact prediction of the overall seismic response and failure mechanisms.

In this context and taking into account that all efforts made for the retrofitting of historical structures should comply with the basic rules of reversibility and respect of the originality of the monument, specialized methodologies for the analysis should be used, in order to achieve a through understanding of the structure's pathology and response before proceeding with any intervention decisions. In this paper three methodologies are presented for the investigation of the seismic response of historical masonry structures. Their application, considering each structure's particularities, can consist of an integrated procedure for the seismic vulnerability evaluation of historical structures and its reduction after protection measures, thus providing an important tool for intervention decisions. The first methodology involves the use of the "FAILURE" software that provides a quantitative description of failure occurring on a masonry structure, subjected to given loading. The second one focuses on the adaptation of the 3D problem of determination of mechanical failure to 2D elasticity assumptions, so as to expand the application of the "FAILURE" software for 3D elasticity considerations. The third methodology is associated with the incorporation of uncertain factors during the seismic vulnerability evaluation and proposes a step-by-step procedure for the probabilistic calculation of structural reliability.

Using these tools, interventions on historical structures can be evaluated. Traditional retrofitting techniques, often, are proved insufficient for effective conservation or restoration. Application of innovative techniques, instead, appears to have a very satisfactory performance, offering a durable, reversible, non-intrusive and long life retrofitting. This paper mainly focuses on the application of dampers. Through hysteretic loops, they have the ability to dissipate external energy, introduced into the structure by dynamic phenomena such as earthquake, and to convert it, mainly, into heat (Casciati and Faravelli 2001). Their use and effectiveness is presented through the analysis of case studies.

2 SEISMIC ANALYSIS OF HISTORICAL MASONRY STRUCTURES

2.1 Stress and failure analysis

During the analysis, particularities of historical masonry structures, in comparison with modern structures have to be considered. Lack of homogeneity of masonry structural materials in contrast with modern industrial materials is typical for such structures, as well as uncertainties concerning the type and quality of connections. These parameters lead to large dispersion of the shear and tensile strength of the masonry. The distribution of structure's masses all over it and the relative insignificance of masses concentrated at the floor levels are additional particularities that do not allow for modern structures assumptions.

The reliability of the analysis model is of very high importance for the validity of analysis results. Extremely detailed representation of the actual state of the structure can often result in misleading conclusions when the original concept of the load-bearing system is not expressed with clarity. Thus detailed modelling is often sacrificed for the achievement of increased levels of reliability. On this basis and given that loading assumptions are made so as to simulate and not to represent with extreme accuracy nature effects, analysis mainly aims at the provision of an indication of the structural performance instead of a unique solution to a given problem.

Analysis is necessary to be performed before and after the retrofitting redesign. In some cases alternative interventions should be investigated through analysis, so as to achieve minimization of intrusiveness and maximization of compatibility.

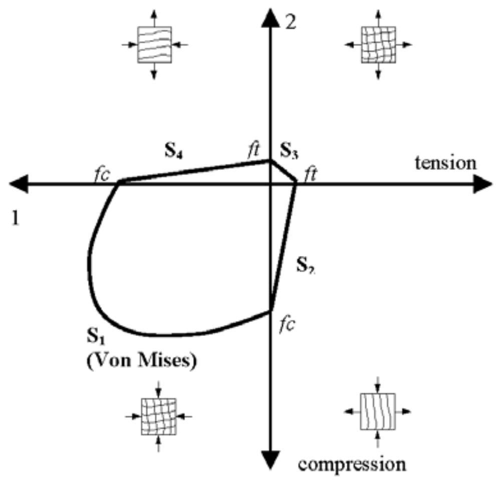

Figure 1 : The modified Von Mises failure criterion.

For the stress analysis of historical masonry structures and monuments, the finite element method (FEM) is highly recommended due to its flexibility in modelling three-dimensional structures and the accuracy of the results obtained. Massive distribution of masonry's self-weight is taken into account by attributing to each finite element a mass that is lumped at the element joints. In this way a satisfactory simulation of the inertia forces during dynamic analysis is obtained. Depending on the structure's particularities and the precision desired many variations of FEM analyses exist, with a main distinction between the detail levels of the composite materials simulation (micro-, meso- and macro-analysis) and the type of finite elements used (one-, two- or three-dimensional).

Failure analysis, following stress analysis, gives an indication of the masonry susceptibility to damage, under specific loading assumptions. For this purpose the modified Von Mises failure criterion is used, as proposed by Syrmakezis and Asteris (2001). The modified Von Mises failure surface is formed by the interaction of four surfaces S_1, S_2, S_3, S_4, as shown in Fig. 1 for zero shear stress. When stresses applied on a finite element wall area are expressed by a point outside the above-mentioned surface, the area is deemed to fail. The "FAILURE" software, also developed by Syrmakezis and Asteris (2001), is used for the elaboration of data and the generation of graphical and statistical outputs, showing the type and location of failure.

2.2 Analysis using three-dimensional finite elements

The architectural and social importance of masonry historical structures imposes high standards concerning the accuracy and the reliability during analysis. The widely used discretization using two-dimensional finite elements (shell, plate or membrane) can be proved insufficient when, after the meshing, finite elements' thickness representing the wall width results to be considerably great in proportion to their area dimensions. Inadequate model formulation using plane finite elements is also observed in the case of architectural particularities, e.g. walls presenting width variations, where assumptions required to effect dimensionality reduction in order to use two-dimensional elements for the analysis, may be proved misleading. In such cases, the use of three-dimensional solid elements is strongly recommended, since it moreover permits the acquirement of data related to stress variation along the width of the structure.

In this paper, a methodology for the failure analysis of models made of solid finite elements is presented. The main objective has been to adapt the 3D problem of determination of mechanical failure to 2D elasticity assumptions, through substitution of the third principal stress by its effect on the other two (Syrmakezis, Antonopoulos and Mavrouli 2005). Calculation of the effect of the eliminated principal stress on the remaining two is based on Hooke's law. The proposed process has to be repeated three times in order to determine equivalent stresses for each plane. In Fig. 2 the principal stresses are shown for the triaxial stress state (left) and its equivalent biaxial (right) after elimination of the principal stress σ_3^T, where the index T denotes the triaxial state and B denotes the respective biaxial one.

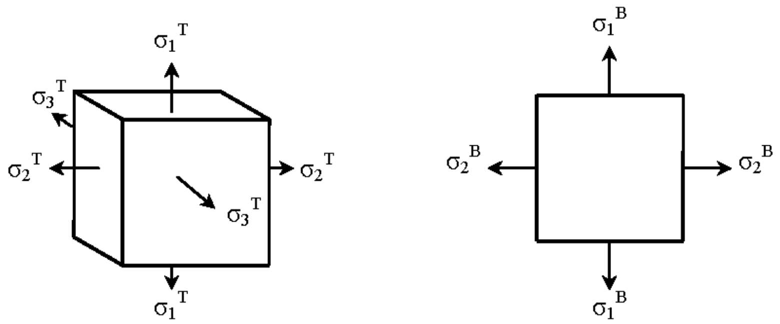

Figure 2 : Principal stresses for 3-D and equivalent 2-D states

Equivalence of the two stress states presumes equivalence of strains, which results in the following transformation equations:

$$\sigma_1^B = \sigma_1^T - v\sigma_3^T/(1-v) \qquad \sigma_2^B = \sigma_2^T - v\sigma_3^T/(1-v) \tag{1}$$

$$\sigma_2^B = \sigma_2^T - v\sigma_1^T/(1-v) \qquad \sigma_3^B = \sigma_3^T - v\sigma_1^T/(1-v) \tag{2}$$

$$\sigma_1^B = \sigma_1^T - v\sigma_2^T/(1-v) \qquad \sigma_3^B = \sigma_3^T - v\sigma_2^T/(1-v) \tag{3}$$

where v =Poisson's ratio

Eqs. (1) correspond to the elimination of σ_3^T and the reduction of the three-dimensional state to the biaxial one (σ_1^B, σ_2^B), Eqs. (2) to the equivalent state (σ_2^B, σ_3^B) and Eqs. (3) to the equivalent state (σ_1^B, σ_3^B). Having obtained the equivalent biaxial stresses, failure analysis is performed as described in paragraph 2.1.

2.3 The probabilistic approach on structural vulnerability

The seismic vulnerability of a structure is associated with its structural performance under a seismic event, through the definition of a correlation function between the earthquake action and the excess of a certain response level. Structural performance evaluation incorporates significant uncertainties that derive from model simplifications, material mechanical properties variations, past interventions, cracks and creeping phenomena as well as the random nature of earthquake or other threat scenarios. As a result, a probabilistic approach to the definition of seismic vulnerability that takes account of these uncertainties can provide a more thorough description of the structural response. In this paper, a procedure for the probabilistic evaluation of historical structures vulnerability through a fragility curves diagram is presented.

The methodology is divided into three main stages (Syrmakezis, Antonopoulos and Mavrouli 2005). The first stage involves the determination of the quantified parameters and their value ranges that serve for the description of the seismic hazard (seismic intensity index), of the structural property presenting varying values (observation parameter) and of the structural response (damage index). Calibration of the response parameter indices is necessary so as to transform quantitative values of the damage index into qualitative descriptions of the damage extent (damage levels). In the second stage, stress and failure analysis are performed so as to acquire response data and in the third one, statistical elaboration of the data is made. A distribution function fitting the data, usually the normal or lognormal is used to calculate the cumulative probability of exceeding each damage level. The fragility curves diagram is generated expressing susceptibility of the structure to damage, under a single seismic event.

3 SEISMIC ANALYSIS USING PASSIVE CONTROL DEVICES

For the dissipation of seismic energy by the application of damper devices, their viscoelastic properties are exploited. Among the three basic models to describe the material behaviour, the Maxwell model, the Voigt model and the standard linear model (Sun and Lu 1995), the Maxwell model is selected, which comprises an elastic and a viscous element combined in series, as seen in Fig. 3.

Figure 3 : The Maxwell model

For the application of a force $F = F_0H(t)$, where $H(t)$ is the Heaviside unit function, suddenly applied and then maintained at a constant value, the deformation u is calculated by Eq. (4):

$$u(t) = F_0\left(\frac{1}{k}+\frac{t}{c}\right)H(t) \tag{4}$$

where k = spring constant and c=viscosity

On the contrary, if a deformation $U = U_0H(t)$ is applied, the force required to maintain it is calculated by Eq. (5):

$$F(t) = U_0 k e^{-\frac{k}{c}t} H(t) \tag{5}$$

4 CASE STUDIES OF HISTORICAL STRUCTURES AND MONUMENTS

4.1 The case of Nea Moni, Chios Island

Nea Moni is a monastery included in the Catalogue of Monuments of the International Cultural Heritage of UNESCO, constructed in the middle of 11th century and situated in the Island of Chios, Greece. The structure involved in this paper, is the church of Agios Panteleimonas, which is conjugated with a semi-underground Cistern. Both of them are masonry structures. The church has a rectangular layout of 14.65x5.25 m^2 and is 7.30 m high. Cistern's height is 6.70 m, its length equals to 18.45 m and its width equals to 11.70 m. A vault roof based on arches covers it. The objective has been to investigate the seismic response of its actual state and to propose a retrofitting intervention.

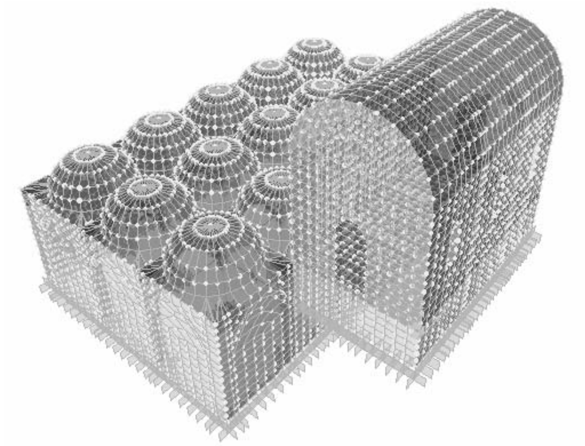

Figure 4 : The finite-element model of Agios Panteleimonas and Cistern

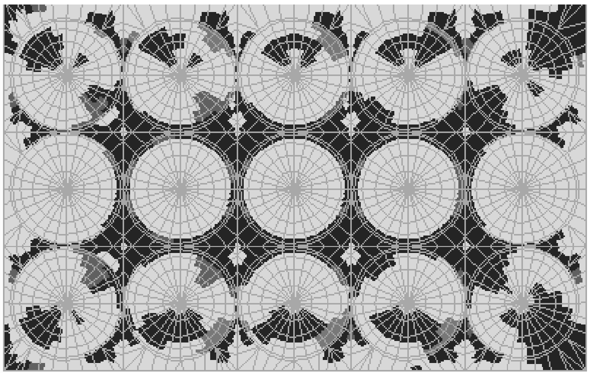

Figure 5 : Failure occurring on the Cistern roof for PGA=0.24g

The finite element model was developed, as illustrated in Fig. 4, using shell elements that activate six degrees of freedom on each node. For dynamic stress analysis a Peak Ground Acceleration (PGA) equal to 0.24g was considered. Failure analysis followed, providing graphical outputs of the type, extent and location of damage under the given earthquake. In Fig. 5, the projection of the Cistern roof is shown, presenting failure areas as dark-shaded. A colour printing distinguishes between types of failure (compression or tension along each axis).

Analysis results revealed extensive damage for the given PGA, so dampers have been introduced into the load-bearing system, on a horizontal plane under the roof of the church and along the Cistern arches. Dampers were simulated using one-dimensional viscoelastic finite elements. The effective damping parameter has been used to describe their response. The reduction of displacements of the church and Cistern roof has been remarkable: up to 33% and 66% respectively.

Reduction of the seismic vulnerability has also been evaluated using a fragility curves diagram. The observation parameter has been selected to be the masonry's strength in tension because of its dependence on the varying mortar quality and its crucial influence on the structure's seismic performance. The damage index was expressed by the percentage of the failed wall area and its values have been acquired though parametric analyses, for diverse values of PGA and tensile strength. Threshold values of the damage index were 10% (for minor damage), 20% (for moderate damage) and 30% (for heavy damage).

In Fig. 6 the fragility curves diagram illustrates the probability of exceeding each damage level. For PGA equal to 0.16g, the probability of exceeding minor damage (marked with a rhomb) is reduced from 94% to 88%, for moderate damage (marked with a triangle) from 53% to 34% and for heavy damage (marked with a single line) from 13% to 5%.

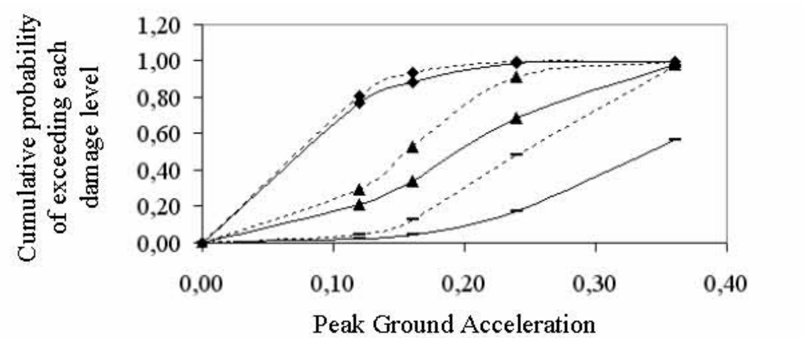

Figure 6 : Fragility curves for the structure, with dampers (continuous line) and without dampers (dashed line)

4.2 The case of a Minaret, Larnaca

The case of a masonry Minaret, part of an Islamic Mosque, situated in Larnaca, Cyprus, has been investigated. The ratio of its height (19.50 m) to its base diameter (2.00 m), puts it among slender structures, characterized by high flexibility and cantilever response.

The analysis model was formed and calibrated, using eigen-period data from vibration measurements at the top of the Minaret. For the rehabilitation of the structure, vertical steel ties, horizontal stiffness ring elements and viscoelastic dampers have been proposed, as seen in Fig. 7.

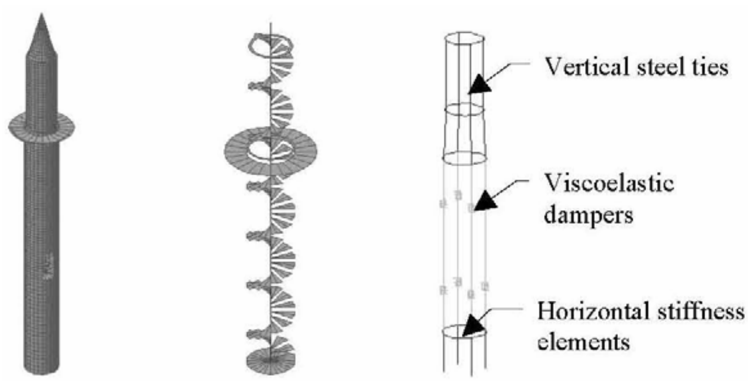

Figure 7 : Analysis model and retrofitting of the Minaret

Dampers have been introduced along the height of the load-bearing system of the structure. Analysis results for the actual and the retrofitted model showed an indicative reduction of the top horizontal displacement due to seismic loading, approximately equal to 30%.

The susceptibility of the structure to damage and the effectiveness of the application of the passive control system have also been investigated through failure analysis. In Fig. 8, failure outputs for the four layouts projections of the Minaret are presented, for seismic force according to the Cyprus Aseismic Code. The improvement of the structural response is significant.

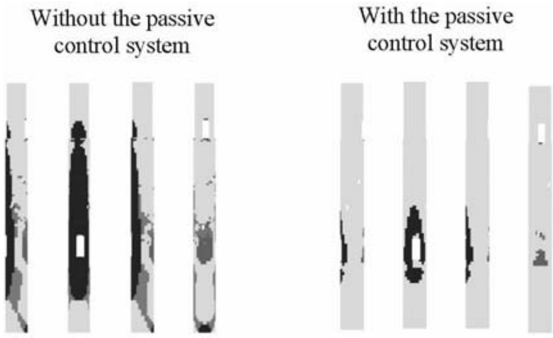

Figure 8 : Reduction of failure areas by using dampers

4.3 The case of a masonry railway bridge, Manari

Manari railway bridge is a curved masonry arch structure, built in late 19th century and consisting part of the secondary railway network of Greece. For its analysis, six-node and eight-node solid isoparametric finite elements were used, so as to acquire detailed out-of-plane stress and failure results, for earthquake loading. Masonry was considered isotropic. Stress analysis was performed only for the actual state of the structure, since the introduction of dampers along its spans, would not lead to improvement of the bridge's seismic response, for out-of-plane loading.

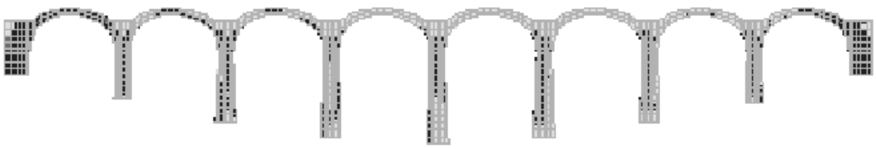

Figure 9 : Failure results due to σ_1^D, σ_2^D

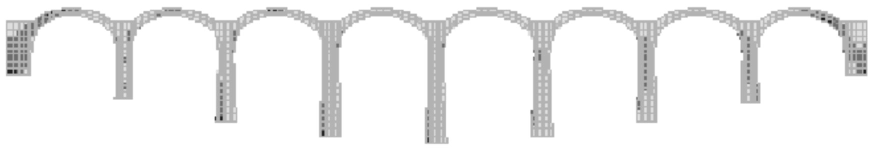

Figure 10 : Failure results due to σ_1^D, σ_3^D

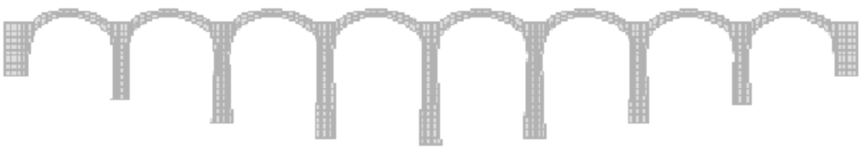

Figure 11 : Failure results due to σ_2^D, σ_3^D

Failure analysis using solid elements was performed according to the methodology presented in paragraph 2.2. In Fig. 9 graphical failure results are illustrated for a longitudinal section on the mid-level of the curved masonry bridge. Failure in this case is owed to σ_1^D, σ_2^D (elimination of σ_3^T). For the alternative considerations of elimination of σ_1^T or σ_2^T, the results are presented in Figs. 10 and 11, respectively. Dark areas representing failure do show the location of failure on the wall surface but they do not show the plane on which failure occurs. Superposition of all three failure cases provides the most unfavourable results vertically to the plane of the bridge.

5 CONCLUSIONS

In this paper, an integrated procedure for the earthquake analysis of masonry historical structures has been presented. Three incorporated methodologies, adapted to masonry have been shown, involving:

- failure analysis using the, especially developed for this purpose, software “FAILURE” that provides graphical and statistical outputs of failure on a wall surface
- the use of the three-dimensional solid finite element for the acquirement of information related to out-of-plane loading and the development of transformation equations for the reduction of the three-dimensional stress state to an equivalent biaxial one
- the vulnerability evaluation through the construction of a fragility curves diagram

All methodologies have been applied for the determination of the seismic response of three types of existent historical structures.

Furthermore, the use of passive control systems for the earthquake mitigation of masonry historical structures has been presented. Analysis of structures retrofitted with dampers has been performed and the effectiveness of the method has been investigated. Stress, failure and vulnerability calculations showed that dampers application can offer a reliable and durable retrofitting, respecting at the same time reversibility and compatibility requirements.

ACKNOWLEDGEMENTS

This paper is presented within the frame of the European project WINDCHIME: Wide-Range Non-intrusive devices toward Conservation of Historical Monuments in the Mediterranean Area.

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