STRUCTURAL STRENGTHENING USING PASSIVE CONTROL SYSTEMS

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ABSTRACT

In this paper, a methodology for the analysis of rehabilitated structures, using the finite element method is presented. The methodology is applied in two directions, either for modern load-bearing system structures or for masonry historical structures and monuments. Structural repair and/or strengthening demands as well as architectural and functional rehabilitation requirements can be satisfied by the use of passive control systems, which are proved to be very efficient in dissipating seismic energy. The methodology for the analysis and vulnerability evaluation of structures using dampers is presented and demonstrated through two case studies, a modern reinforced concrete and an historical masonry structure.

Keywords: strengthening, finite-element analysis, dampers, historical structure, passive control system

INTRODUCTION

In Greece, as well as in the entire of the Mediterranean basin, earthquake structural design is of prior importance, due to the high seismicity of the area. National and international regulations used impose continuously increased levels of safety, especially after major earthquake events with considerable casualties. In the case of existing structures, modern and historical, strengthening involves interventions made into their load-bearing system for the improvement of its overall strength and ductility. The need for such measures derives mainly from:

• past damage that a structure has suffered due to applied static or dynamic actions
• deterioration of structural materials, structural fatigue and creeping phenomena, often encountered in old structures
• modification of operational loads, because of new functional demands and/or architectural rearrangements
• enforcement of new laws or recommendations imposing stricter structural performance criteria in comparison with the previous ones.

The design of structural strengthening mainly lies in the correlation of the seismic performance with the expected earthquake loads and aims to ensure the satisfactory earthquake response of the structure. For this purpose, analysis of the load-bearing system has to be performed in two stages: initially prior to any intervention measure, for the structural identification and the evaluation of the actual state of the structure and then, on the strengthened structural model, in order to verify the improvement of its performance at the desired levels.

Modern concepts for the evaluation of the structural response are based on a probabilistic approach (instead of a deterministic one) that takes into consideration significant uncertainties that derive from model simplifications, material mechanical properties variations, past interventions,

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cracks and creeping phenomena as well as the random nature of earthquake or other threat scenarios, etc. In that case, parametric analyses and statistical elaboration of the results are needed for the determination of the seismic vulnerability.

For the selection of the appropriate strengthening technique the following parameters should be taken into consideration: the type of the load-bearing system, the desired level of seismic performance, the importance of the structure, the cost and time of the interventions, the availability of adequate technology, and additionally, in the case of historical structures and monuments, the ethic principles of restoration/conservation. The use of passive control systems such as dampers satisfies the above-mentioned criteria, in many cases of structural strengthening. Their incorporation into the load-bearing system of a structure results in the removal of the seismic input energy from the structural vibration and its conversion into heat. The benefits of such a transformation of energy are interpreted either, on a short term basis, into reduction of failure and diminution of displacements or, in the long run, into reduction of the structural fatigue and increase of the structural life.

In this paper, a methodology for the analytical evaluation of the response of rehabilitated/retrofitted structures is presented. Its application is demonstrated through two case studies, a modern structure with a reinforced concrete load-bearing system and an historical masonry structure. Particularities encountered for each case are discussed and the efficiency of dampers application is demonstrated.

**THE STRENGTHENING PROCEDURE**

Before proceeding with any intervention action, basic steps of the strengthening procedure have to be followed. Initially, site investigation and collection of general data concerning the geology, seismicity, climate of the area etc. have to be made.

In the following, the collection of architectural, structural and material data is necessary, in order to evaluate the structure’s actual state. The twofold significant importance of the influence of environmental actions on the structure should also be taken into consideration. Firstly because it provides information about the structural pathology and then, because of the fact that for the effective retrofitting, the elimination of factors causing damage should be aimed at.

Following the afore-mentioned tasks, analysis has to be performed twice: for the actual state of the structure in order to acquire a full insight into the response of the load-bearing system and its stress state and after the retrofitting design, so as to verify that the desired performance levels have been ensured. Redesign has to be based on the response results of the actual structural state, so that minimization of interventions and optimization of their efficiency is achieved.

For the redesign one or more loops comprising the conception, the simulation and the determination of simulation assumptions, the stress and failure analysis and the evaluation of the results have to be made, for one or more retrofitting proposals.

**MODERN AND HISTORICAL STRUCTURES PECULIARITIES**

Historical structures present some peculiarities in comparison with modern structures that should be taken into account either with regard to simulation assumptions made or for the selection of the appropriate rehabilitation method.

Masonry, as a composite material consisting, mainly, from blocks and mortar, is characterized by non-homogeneity. In contrast, modern structures such as reinforced concrete (R/C) ones are more homogeneous, permitting the assumption of macroscopic homogeneity of the material. Additionally, while in modern structures industrial materials with standardized mechanical properties are used, in the case of historical masonry structures, usually, in lack of standardization, composite materials present large variability and, in this way, large dispersion of mechanical properties values is observed. Actually, in the latter case, the quality of construction is a determining factor for the assumptions made for the simulation of the load-bearing system, while for modern structures, the standardization of materials and construction techniques do not permit large variability of the mechanical properties, all over the structure.

Although in modern structures, the construction of monolithic connections among structural elements can be ensured, in historical masonry structures, connections are not always monolithic and, different boundary conditions have to be assumed.
Another important difference is related to the distribution of mass. In modern structures, mass is, usually, concentrated on the floor levels. In contrast, masonry structures are characterized by distribution of their mass at the whole of the load-bearing system. This should be taken into consideration for the construction of the simulation model used for the dynamic analysis, since the distribution of inertia forces is critical for the dynamic response of the structure.

As far as it concerns their earthquake performance, masonry structures appear to be more vulnerable to earthquake actions. This is owed to their, usual, low tensile strength (depending mainly on the mortar properties). For modern structures, such as R/C or steel ones, instead, high values of strength in tensile can be achieved, resulting in satisfactory seismic response levels.

When it comes to structural strengthening, the criteria for the selection of the appropriate technique are significantly different. For historical structures, priority is given to the respect of the originality of the structure, thus interventions should be oriented to provide reversibility, compatibility (of materials, load-bearing system and architectural features) and minimization of the interventions. On the contrary, the selection of the intervention technique for modern structures is more flexible and is, usually, based on cost, time and intervention efficiency parameters.

**STRUCTURAL STRENGTHENING USING DAMPERS**

For the dissipation of seismic energy by the application of damper devices, their viscoelastic properties are exploited (Casciati and Faravelli, 2001).

During the design procedure, it should be taken into account that the dissipation of seismic energy is closely related to the specifications of the damper elements. The seismic energy dissipation and the limitation of deformations depend on the structure properties as well as the damping and stiffness properties of the incorporated dampers. The interaction of all these characteristics is also important for the final response of the structure.

**CASE STUDIES**

**Section B of the hospital complex “Agios Andreas”, Patras**

**Description of the structure**

In this case study the response of the hospital building named section B in the hospital complex “Agios Andreas”, in Patras, Greece, has been investigated. The four-story building was initially designed and constructed in the ’60s. It has a reinforced concrete load-bearing system, as seen in Fig. 1.

![Figure 1. Section B of the hospital complex “Agios Andreas”](image)

Due to its location at one of the most high-risk seismic areas of Greece, the structure has suffered several past earthquakes of diverse intensity. The resultant damage involves wall cracks, detachment of infill walls from the load-bearing system, load-bearing members cracks, as well as reinforcement...
corrosion due to humidity. Close observation of the damage reveals that there is a strong possibility of the structure being incapable of withstanding, on an operational level, future earthquake actions.

**Evaluation of the actual structural state**

In order to evaluate the hospital’s actual structural state, seismic analysis had to be performed on a three-dimensional finite element model of the reinforced concrete structure (Fig. 3), consisting of 2,064 linear elements, 10,023 shell elements and 10,674 joints. SAP2000 V.9 software was used (Syrmakesis, Mavrouli and Antonopoulos, 2006).

![Figure 3. Model meshing.](image)

Material mechanical properties were determined with non-destructive methods such as ultrasonic and hammer Schmidt testing, after statistical processing of the data. Final values were estimated as followed: Concrete’s strength in compression fck=12,00MPa, Young’s Modulus Ecm=26GPa, concrete’s self-weight γ=25KN/m3 and steel reinforcement’s strength in tension fsy=220Mpa. Reinforcement detection was made using ultrasonics.

Static and seismic loads were defined according to the actual Greek Aseismic Code and a Peak Ground Acceleration equal to A=0,24g, for the seismic zone of Patras, was considered. Response Spectrum analysis has been performed for a coefficient of importance equal to 1,30, as defined for hospital buildings.

Seismic analysis results revealed that a significant number columns and the majority of the beams have insufficient reinforcement, especially on the basement and on the second floor. This fact increases the vulnerability of the hospital and imposes the application of an intervention method for the strengthening of the building.

| Joint ID: 5842 Earthquake along y-axis Absolute Max. Displacements |
|-------------------------|----------------|----------------|
| Ux (cm)                 | 2,98           |
| Uy (cm)                 | 20,99          |
| Rz (rad)                | 20,00116       |

Table 1 presents some indicative results of the analysis: maximum displacements due to earthquake loading, of a joint on the highest level, in the middle of the layout of the building.
Selection of the repair and strengthening technique

Besides the earthquake protection of the building, minimization of displacements was desired, in order to avoid failure of electro/mechanical equipment, during an earthquake event. For the repair and strengthening of the hospital, two options were considered. The first one was a conventional reinforcement method, using concrete jackets for the increase of beam and column section dimensions and the second one involved an innovative technique, using a passive control system consisting of damper braces. However, required intervention to the hospital building, without any interruption of its operation can only be satisfied by the application of the second solution. Analysis was performed for both cases and comparative results were obtained.

Reinforcement using concrete jackets

In order to improve the overall strength of the hospital, the increase of the dimensions of the sections that have been found insufficient by structural analysis, has been investigated.

<table>
<thead>
<tr>
<th>Joint ID: 5842</th>
<th>Earthquake along y-axis</th>
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<tbody>
<tr>
<td></td>
<td>Absolute Max. Displacements</td>
</tr>
<tr>
<td>Ux (cm)</td>
<td>1.98</td>
</tr>
<tr>
<td>Uy (cm)</td>
<td>14.16</td>
</tr>
<tr>
<td>Rz (rad)</td>
<td>0.00090</td>
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</table>

Concrete jackets with adequate steel reinforcement were considered for the increase of the moment of inertia of linear elements, and analysis was performed for the new structure. The width of the concrete jacket was designed to be 5 cm. Absolute maximum displacements of joint 5842, for earthquake loading along y-axis are shown in Table 2.

Reinforcement using damper braces

High standards imposed for large energy dissipation, can be satisfied by the effective utilization of passive control systems. As a result, redesign of the building was performed using viscoelastic dampers.

Figure 4. Damper braces placement on the typical floor plan.
A bracing system was introduced along the height of the building (the height of each floor is 3.10m), in 16 different positions, along both directions, respecting, at the same time, architectural particularities and operations of the building.
Locations of the braces are shown in Fig. 4 (numbers in circles), while in Fig. 5 two views of the building (transversal, A and longitudinal, B) are illustrated, presenting placement of dampers along its height.

The response of dampers was simulated by the Maxwell linear model of viscoelasticity, with effective damping equal to 5000KN·sec/m. New analysis results were obtained. Absolute maximum displacements for joint 5842, for earthquake loading along y-axis, are shown in Table 3.

![View A and View B](image_url)

**Figure 5. Damper braces placement along the building’s height.**

**Table 3. Indicative displacements of the retrofitted with damper braces structure**

<table>
<thead>
<tr>
<th>Joint ID: 5842</th>
<th>Earthquake along y-axis</th>
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<tr>
<td></td>
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<td>Uy (cm)</td>
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<td></td>
<td>Rz (rad)</td>
</tr>
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**Comparative results**

The modification of the seismic response is expressed through comparative absolute maximum displacement results of the considered joint, 5842.

![Displacements Ux, Uy](image_url)

**Figure 6. Indicative displacements for earthquake loading.**
Fig. 6 illustrates results for displacements Ux and Uy, while Fig. 7 shows the calculated rotation $R_z$ for each of the three models. The loading combination corresponding to earthquake along y-axis is considered.

These charts also present the reduction of the calculated deformations for both retrofitting techniques. The reduction of horizontal displacements for the application of damper braces is remarkable. An important but smaller reduction is also noticed in the case of the concrete jackets use.

Concerning the x-axis, small displacements were observed even before the interventions, which are further reduced by the application of both reinforcement techniques.

**The case of Nea Moni, Chios Island**

*Description of the structure*

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 (Fig. 8). 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 (Marinelli, Syrmakezis and Antonopoulos, 2004). The objective has been to investigate the seismic response of its actual state and to propose a retrofitting intervention.

![Figure 8. (a) Agios Panteleimonas church (b) The internal of the Cistern.](image)
Stress and Failure analysis of the structure

The finite element model was developed as illustrated in Fig. 9 using plane shell elements that activate six degrees of freedom on each node. For the dynamic stress analysis a Peak Ground Acceleration (PGA) equal to 0.24g was considered.

Figure 9. The finite-element model.

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 was 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. 10 for zero shear stress.

Figure 10. Modified Von Mises failure criterion for masonry.

The “FAILURE” software, Syrmakezis and Asteris (2001), was used for the elaboration of data and the generation of graphical and statistical outputs, showing the type, extent and location of failure. In Fig. 11, the projection of the Cistern roof is shown. Red areas have failed under biaxial tension, green areas under biaxial tension/compression and cyan area remain unaffected.

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, as seen in Table 4.
Table 4. Indicative displacements of the un-retrofitted and the retrofitted structure

<table>
<thead>
<tr>
<th>Absolute Maximum Displacements</th>
<th>Joint ID: 2117 (church)</th>
<th>Joint ID: 5528 (Cistern)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>un-retrofitted</td>
<td>retrofitted</td>
</tr>
<tr>
<td>Ux (cm)</td>
<td>0,29</td>
<td>0,19</td>
</tr>
<tr>
<td>Uy (cm)</td>
<td>0,50</td>
<td>0,05</td>
</tr>
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</table>

**Evaluation of vulnerability**

Referring to structural control and restoration of historical structures and monuments, high demands are raised, due to their great significance as cultural heritage carriers. Economical, social and architectural motives impose the need of a clear insight into structural reliability, for decision-taking purposes. At the same time, the random character of properties that determine the structure’s capacity to resist loads and the difficulty in establishing the magnitude of anticipated loads, lead to a probability-based design approach.

Seismic vulnerability of structures is associated with their expected performance when subjected to a single seismic event, through the definition of a correlation function between this action and the probability of exceeding a certain response level, accounting, at the same time, for random values of a structure’s property referred to as the observation parameter. The illustration of this function takes place through a fragility curves family diagram, developed by using response parameter distributions calculated from the analyses of structural models under increasing earthquake loads (Syrmakezis, Antonopoulos and Mavrouli, 2005).

Figure 12. Fragility curves for the structure, with dampers (red) and without dampers (black)
For the monument under consideration, the observation parameter has been selected to be the masonry’s strength in tension because of its strong 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 through 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. 12 the fragility curves diagram illustrates the probability of exceeding each damage level, for the retrofitted and the un-retrofitted structure, revealing the improvement of its seismic response. For a PGA equal to 0.16g, the probability of exceeding minor damage is reduced from 94% to 88%, for moderate damage from 53% to 34% and for heavy damage from 13% to 5%.

CONCLUSIONS

In this paper structural retrofitting using passive control devices has been presented. The application of damper elements has been investigated either for modern or for historical structures. Particularities of each of the two types, affecting the mechanical structural properties, the modelling simulation assumptions and the conception of the retrofitting design, have been presented.

The procedure of structural analysis and design, using dampers, has been demonstrated through two case studies: a modern reinforced concrete structure, “section B” of Agios Andreas hospital, and an historical masonry one, the Agios Panteleimonas church and its conjugated Cistern. In the first case, non interruption of the hospital operation is desired, which can only be satisfied by retrofitting, incorporating damper braces into the load-bearing system of the structure. The application of this retrofitting technique can also satisfy the criterion of minimization of displacements, in order to avoid damage of electro-mechanical equipment. As calculated by analysis, displacements along the earthquake loading direction have been reduced at 49,12% of the actual structure displacements, while, for the construction of concrete jackets the respective value has been equal to 67,46%.

For the historical structure, requirements related to reversibility and compatibility of interventions can be met by the use of dampers. The evaluation of the vulnerability reduction has been demonstrated through a fragility curves diagram an dampers have been proved to significantly improve the seismic response.

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REFERENCES


