Seismic isolation: a new approach to earthquake protection of historic monuments

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ABSTRACT: Seismic isolation, as a new approach to earthquake-resistant design, has been applied mostly to new buildings, but there are a small number of examples of its application to already existing buildings. This paper presents results from investigations performed within the research project “Earthquake Protection of Byzantine Churches Using Seismic Isolation”, which main objective was development of a methodology for application of seismic isolation in Byzantine churches represented by an imposing number of historic monuments located in the Balkan and the Mediterranean region. The tests proved that the new, specially developed system of seismic base isolation of historic monuments offers absolute safety and protection and that its application should become an imperative in earthquake protection of historic monuments in future.

1 INTRODUCTION

Traditional stone and brick masonry structures, whether or not they are historic monuments, have low ductility, and, due to their stiff and brittle structural components, are usually severely damaged during strong earthquakes. The main reasons for damage or collapse are the lack of ductility of the masonry components, high displacements that the structure cannot afford, and amplification of dangerously high frequencies due to their dynamic behaviour in response to earthquake action making them vulnerable to those harmonies of the ground motion.

In order to improve the behaviour of these masonry structures in response to earthquake forces, strengthening measures that emphasize the use of reinforcing steel have been widely adopted in building codes. In this practice, steel reinforcement is placed within piers and walls at critical areas to compensate for the lack of tensile strength and ductility and to increase the stiffness of these elements. Horizontal bands are provided at different levels in order to ensure “box-like” action and to reduce the possibility of “out-of-plane” failures. These strengthening concepts have met with success by greatly decreasing the potential of collapse.

However, these methods are quite intrusive, may require the partial disassembly of building elements, can destroy valuable and irreplaceable interior finishes, and can also alter the external appearance of a building. In spite of these interventions, masonry structures can still be cracked during earthquakes of medium or higher intensity. Therefore, alternative design philosophies for seismic strengthening need to be explored for historic masonry structures where the conservation of historic fabric is paramount.

2 CONCEPT OF BASE ISOLATION AND ITS APPLICATION IN CULTURAL HERITAGE

Seismic base isolation would appear to be an attractive alternate to the widely adopted seismic strengthening techniques discussed above. With base isolation seismic loads can be reduced to the same order of magnitude as the existing strength of the historic buildings and this in turn will decrease and may eliminate altogether the need for intervention above the level of isolation. In this manner, the interior and exterior fabric can be left undisturbed. With base isolation, a major part of the earthquake energy that would have been transferred into the building structure would be absorbed at the base level. Consequently, ductility demand to the structure is greatly reduced; displacement would be strictly controlled by the addition of an appropriate amount of damping within the base isolation system; and the frequency of the isolated structure
is decreased to a value below that which dominates in a typical earthquake. So the three damaging criteria discussed above, lack of ductility, high displacements, and amplification of high frequencies are addressed.

The application of the technique of base isolation to increase the seismic safety of masonry structures with high cultural-historic value is promising where other possible strengthening techniques do not seem to be applicable.

Historic buildings tend to have structural systems that are stiff but brittle, and their dynamic behaviour preferentially amplifies high frequency motion, making them vulnerable to those harmonics of the ground motion. The use of an isolation system protects the structural system from the most dangerous frequencies by transferring the demands that would have been placed on the structure to the isolation system.

In the concrete case, a question arises as to what are the advantages and flaws of applying this methodology on historic monuments?

The main advantages of this methodology are:

- The complete intervention (construction work) is done at the foundation level so that only conservation work is done on the existing upper structure.
- The fresco-paintings on all the walls of the interior of churches is maximally protected against possible damage in the course of structural strengthening of the structures so that the process of fresco-conservation and protection runs independently of the structural intervention.
- A great number of churches that possess extremely valuable frescoes, are quite small in size. Seismic isolation is very efficient and simple for their conservation.

The flaws of the above methodology are the following:

- The intervention carried out by incorporation of devices for seismic isolation at the foundation level represents a huge task that modifies, in a certain way, the basic concept of the existing structure. This represents a problem in the sense that conservators have to accept this as a possible way of protection in each concrete case.
- The isolation devices are modern technological products, which are quite costly and are produced by specified companies. The cost of seismic protection by application of such devices is higher than that of traditional seismic protection. However, for historic monuments, it is difficult to estimate the cost of such a protection since seismic isolation has so far been done on a very limited number of monuments.

As a conclusion, it must be pointed out that application of seismic isolation in historical buildings is recommendable and its wider application should be expected in future. In addition the cost of the base isolation, due to its advancement, has decreased significantly.

3 EXPERIMENTAL INVESTIGATIONS OF THE BASE ISOLATED MODEL M-SN-BIC

To develop appropriate approaches for repair and strengthening of Byzantine churches, in general, and particularly churches located within Macedonia, research projects on seismic strengthening, conservation and restoration, including seismic isolation of Byzantine Churches in the Republic of Macedonia were realized in the period 1990–2000, (Gavrilovic et al. 1995). The development of a methodology for application of seismic isolation in Byzantine churches represented by an imposing number of historic monuments located in the Balkan and the Mediterranean region, is the main objective of the research project “Earthquake Protection of Byzantine Churches Using Seismic Isolation”, (Gavrilovic et al. 2001). Taking into account the specific characteristics of the structures and the investigations that have so far been performed for the needs of application of this methodology, performance of analytical and experimental investigations with defined criteria and conditions for application becomes a necessity.

In the process of design of seismic isolation for protection of cultural historic monuments, variant solutions of different systems and isolation methods have been analyzed, with a particular attention focused on the model to be tested and application in existing structures. In addition to the methods and ways of seismic isolation by use of modern technologies, particular emphasis was put on possible isolation by use of natural materials. Based on the results from the analytical investigations performed by use of corresponding models of dynamic response of structures whereas data from literature and performed experimental investigations were used as input characteristics of the isolation systems, it may be concluded that the isolation systems with natural material (gravel, sand and alike) offer limited possibilities considering their physical characteristics (friction), whereas the application of a modern equipment offers the possibility for controlled behaviour of the structures depending on their characteristics and the characteristics of the equipment.

The objective of the project was not development of a new isolation system for historic monuments but to choose one from corresponding systems and apply it, focusing on specific behaviour of the structures and buildings pertaining to historic monuments.

Taking into account the previously acquired knowledge, the practice and the main assumptions from the aspect of analytical and experimental behaviour of the system on one hand, as well as the specific criteria
and requirements regarding protection of historic monuments on the other hand, new, specially developed system, or better to say, concept of isolation within the framework of the investigation project is "laminated rubber bearing with steel dampers and stopper elements", (Fig. 1).

The schematic presentation of the system clearly distinguishes three main elements:

A. Laminated rubber bearing element for receipt and transfer of vertical gravity forces and limited displacement (insulation) in horizontal direction (element 1).

B. Steel plate damper (element 2) which has the role of a damper in the form of hysteretic behaviour but only after the linear behaviour of the laminated rubber bearings is exhausted. This element is different from the other systems by being not activated in the first phase of linear behaviour of the laminated bearing isolators but in the second phase under higher excitation expected to induce large displacements.

C. In conditions of specific behaviour and requirements for historic monuments regarding their protection in seismic conditions, one of the elements is "limited displacement". This criterion is satisfied by design of the third element of our system – "stopper element".

In this way, the main requirements are satisfied as to linear behaviour of the system (meaning without damage and deformations) under slight and moderate earthquakes and its limited but controlled displacements by activation of elements 2 and 3 (hysteretic dampers and stopper elements) under catastrophic earthquakes. This enables complete protection of the structure and the valuable objects within the structure like frescos and other elements.

For this system and according to the main characteristics of the structure (weight, stiffness and expected-desirable behaviour), a total of 8 bearings with their main characteristics have been specially designed with characteristics as given in Table 1. They have been completely manufactured in R. Macedonia and prepared for shaking table tests combined with corresponding steel stoppers that have been fixed, (Figs 2–3).

<table>
<thead>
<tr>
<th>Table 1. Characteristics of optimized seismic isolators.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular cross-section with</td>
</tr>
<tr>
<td>$D = 13.1 \text{ cm}$</td>
</tr>
<tr>
<td>Total height</td>
</tr>
<tr>
<td>Total number of rubber elements</td>
</tr>
<tr>
<td>Total number of steel sheets</td>
</tr>
<tr>
<td>Thickness of the rubber element</td>
</tr>
<tr>
<td>Thickness of the steel sheet</td>
</tr>
<tr>
<td>Sliding modulus of the rubber element</td>
</tr>
<tr>
<td>Stiffness of an isolator</td>
</tr>
<tr>
<td>Stiffness of a system of 8 isolators</td>
</tr>
<tr>
<td>Mass of the church model</td>
</tr>
<tr>
<td>Expected (designed) period of the base isolated model</td>
</tr>
<tr>
<td>$(T = 0.60 \text{ sec}$</td>
</tr>
</tbody>
</table>

Figure 1. Laminated rubber bearing for seismic isolation.

Figure 2. Seismic isolator with steel stopper.

Figure 3. View of seismic isolator in action.

For such a selected isolation system, detailed analytical investigations have been performed for different levels of input acceleration and for different earthquake records. Designed and constructed for the optimal system of a total of 8 isolators has been a steel structure for connection of the isolators with the church model structure and the seismic shaking
The base isolated model, labeled M-SN-BIC, was then placed on a shaking table on a specially designed steel structure for connection with the isolators on the shaking table, (Fig. 5).

The model was subjected to the same series of dynamic tests as for the previously tested original (M-SN-EXIST) and strengthened model (M-SN-STR), (Gavrilovic et al. 1995). However, due to the base energy dissipation characteristics of the base isolated model, the tests were also continued at higher intensities. An analysis of results obtained from the test is given in Table 2.

### Table 2. Results of the model M-SN-BIC for different intensities of El Centro earthquake.

<table>
<thead>
<tr>
<th>Input</th>
<th>Foundation</th>
<th>Base of the tambour</th>
<th>Top of the dome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc (g)</td>
<td>Disp (mm)</td>
<td>Acc (g)</td>
<td>Disp (mm)</td>
</tr>
<tr>
<td>0.17</td>
<td>9.0</td>
<td>0.06</td>
<td>11.0</td>
</tr>
<tr>
<td>0.30</td>
<td>18.0</td>
<td>0.09</td>
<td>23.0</td>
</tr>
<tr>
<td>0.41</td>
<td>27.0</td>
<td>0.13</td>
<td>32.0</td>
</tr>
<tr>
<td>0.49</td>
<td>33.0</td>
<td>0.21</td>
<td>44.0</td>
</tr>
<tr>
<td>0.54</td>
<td>36.0</td>
<td>0.26</td>
<td>48.0</td>
</tr>
<tr>
<td>0.63</td>
<td>42.0</td>
<td>0.30</td>
<td>63.0</td>
</tr>
</tbody>
</table>

### 3.1 Comparative analysis between experimentally obtained results

Table 3 shows the comparison between experimentally obtained results for all three models, i.e. between previously tested original, nonretrofitted model (M-SN-EXIST) and strengthened model by use of “ties and injection” (M-SN-STR), (Gavrilovic et al. 1995), and the base isolated model (M-SN-BIC), (Gavrilovic et al. 2001, Gavrilovic et al. 2002, Gavrilovic et al. 2003).

From the comparison of the experimental results the following can be concluded:

- The results from these tests, especially compared with the results from the previously tested strengthened model by use of “ties and injection”, pointed to a decrease of input acceleration in the model structure for 50-60%.
- It was evident that the output displacement and acceleration through the height of the base isolated model were considerably smaller than that for the strengthened model.
- There is also significant difference in the amplification of the dynamic response of the dome structure, in the case of M-SN-BIC it was negligible.
- The failure mechanism of the base isolated model is completely different from the previous models. For all testing up to input acceleration of 0.60 g, the base isolated model behaves as a rigid body without any visible cracks. When the cracks formed they were in a pattern similar to those of the original model.
- The base isolated model did not suffer damage under low and moderate earthquake intensities and the damages under maximum expected accelerations with a return period of 1000 years, \(a_{\text{max}} = 0.54 \text{ g}\) were minimal and absolutely allowable and repairable.
- Finally, to conceive the efficiency of the applied seismic isolation system, the model was tested under earthquake intensity greater than the expected one, (El Centro, \(a_{\text{max}} = 0.63 \text{ g}\)). Under this intensity, the
Table 3. Comparison between the experimental results of three models.

<table>
<thead>
<tr>
<th>Earth quake</th>
<th>Input acc (g)</th>
<th>Output acceleration (in g) for the church models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-SN-EXIST</td>
<td>M-SN-STR</td>
</tr>
<tr>
<td></td>
<td>Level 1 Level 2</td>
<td>Level 1 Level 2</td>
</tr>
<tr>
<td>El Centro</td>
<td>0.17 0.29 0.55</td>
<td>0.20 0.47</td>
</tr>
<tr>
<td>El Centro</td>
<td>0.30 – –</td>
<td>0.65 1.10</td>
</tr>
<tr>
<td>El Centro</td>
<td>0.49 – –</td>
<td>0.91 1.59</td>
</tr>
<tr>
<td>El Centro</td>
<td>0.54 – –</td>
<td>0.77 1.41</td>
</tr>
<tr>
<td>El Centro</td>
<td>0.63 – –</td>
<td>– –</td>
</tr>
<tr>
<td>Petrovac</td>
<td>0.19 0.39 0.76</td>
<td>0.27 0.48</td>
</tr>
<tr>
<td>Petrovac</td>
<td>0.40 – –</td>
<td>0.77 1.36</td>
</tr>
<tr>
<td>Breginj</td>
<td>0.17 0.22 0.52</td>
<td>0.30 0.55</td>
</tr>
<tr>
<td>Breginj</td>
<td>0.28 – –</td>
<td>0.20 0.40</td>
</tr>
<tr>
<td>Breginj</td>
<td>0.38 – –</td>
<td>0.34 0.79</td>
</tr>
</tbody>
</table>

* Level 1 – Base of the tambour.
* Level 2 – Top of the dome.

monument was evidently stable and safe, with the exception of some minor damage.

4 IMPLEMENTATION OF THE RESULTS IN REAL HISTORIC MONUMENTS

One of the main tasks and problems in repair and/or strengthening in the process of reconstruction and protection of historic monuments in seismic regions is to answer the question as to how far we should go as to the level of safety on one hand and the extent of the intervention on the other.

Modern approach to protection of cultural heritage should be a multidisciplinary one sticking to the maxim of "minimum intervention – maximum protection", which should serve as a basis for introducing of criteria for protection against earthquake effects considering all the specificities of the site and the expected level of seismic effect as well as the specific characteristics of the monuments, their historic, cultural importance, their structure and characteristics of materials used for their construction.

The criteria for seismic protection by application of seismic isolation could be summarized as follows:

- the structure is to suffer no damage under slight seismic effects with a return period of 200 to 300 years.

The above criteria cannot be easily realized by traditional ways of repair and strengthening. However, the application of new technologies as is seismic isolation can enable their complete realization.

Prior to definition of requirements and criteria, let us point out some principal features and factors favoring seismic isolation in historic buildings and monuments.

- Isolators may give large reductions in the seismic loads and deformations for those structures, with short periods and low dampings, which are most prone to suffer severe seismic attack if unisolated.
- Selected isolators may give very large reductions in the seismic loads on secondary structures and on the contents of appropriate structures.
- An isolator which is effective in reducing seismic attacks on a structure must have features which result in relatively large isolator displacements. The total structural displacements are then a little larger than the displacements of the supporting isolator, since they are moderately increased by structural deformation.

In applying seismic isolation of historic buildings and monuments, it is evident that the principle "minimal intervention – maximum protection" is completely fulfilled.
should be thoroughly preserved, minimal cracks that would be easily repairable could be allowed.

- Under all the remaining effects (return period of 500 years), the structure should be completely non-vulnerable and behave in the elastic range.

These criteria have been proved through experimental investigations, appropriate design of isolators and the process of corresponding design.

The conditions for application of seismic isolation as a methodology are practically not limited, but to achieve stability of the structure “over the isolators”, the conditions referring to the integrity of the structure should be preserved whereat torsional effects, relative vertical displacements and horizontal displacements of individual parts as well as the amplification effects should be minimized and controlled.

Protection via seismic isolation of historic buildings and monuments should be carried out by fulfillment of the following requirements and conditions:

- Definition of seismic hazard, geological and geotechnical conditions at the site;
- Analysis of the existing state of the structure resulting in identification of the structural system and built-in materials;
- Definition of safety criteria and required level of protection of the integral structure as well as its separate parts or works of art (if they exist);
- Preliminary design and selection of isolation system and devices;
- Design of isolation, modeling and analysis of the structure for the expected seismic effect;
- Final design and necessary interventions on the principal system (repair and/or necessary local strengthening);
- Construction and supervising by persons competent in the field.

5 PRELIMINARY DESIGN OF SEISMIC BASE ISOLATION SYSTEM FOR THE ROTOTYPE CHURCH OF ST. NIKITA

5.1 Existing seismic stability of the St. Nikita church

The church of St. Nikita in the village of Banjani has been selected as a prototype church representative of the Byzantine churches in Macedonia. Typologically, it represents a single-dome church with a developed cross inscribed in a rectangular plan. The structural system of the church consists of massive peripheral walls in both orthogonal directions (with a thickness of about 85 cm and constructed partially of hewn stone and brick) and two rows of symmetrically placed columns, supports over the vaulted roof elements and a central dome (Fig. 6). All the wall areas in the interior are flat and painted by the known fresco-painters of that time – Michael and Eucthios (14th century). These frescoes are preserved to a larger extent, particularly in the lower and central parts of the church. The walls of the building are original, in principle, and date back from the 14th century. They are constructed in a typical Byzantine style – a wall with two faces between which there is an infill of lime mortar and pieces of bricks and stone.

The present state of the building is good from the aspect that the roof satisfies the requirements for protection against leakage. The effect of capillary moisture is also negligible. The building structure may be considered stable. Neither severe cracks nor extensive deformations are observed.

Within the previous project (Gavrilovic et al. 1995), ample field and analytical studies, in situ and laboratory tests were performed for the existing structure
of the prototype church of St. Nikita for the purpose of defining the physical-mechanic and chemical characteristics of the built-in materials, the dynamic characteristics of the structure and the seismicity of the terrain. An analysis of the seismic stability of the existing structure was performed to estimate the ultimate bearing and deformability capacity for different intensities and types of seismic excitations. To model the existing structure, a mathematical model that is usually applied for analysis of masonry structures in engineering practice was used in static analysis. In dynamic analysis, the structure was idealized as a single-degree-of-freedom system and analyzed with computer programmes that have been developed in IZIIS.

Performed for the existing structure of St. Nikita church was a response analysis under three levels ($0.12 \, g$, $0.20 \, g$, $0.34 \, g$) of maximum input accelerations of Petrovac and El Centro earthquake, in both orthogonal directions. The results point to failure of individual secondary elements and occurrence of severe damage to the bearing walls, $(1.5 < \mu < 2.5)$, even under earthquakes of $t_p = 200$ years, ($a_{\text{max}} = 0.20 \, g$). Under earthquakes of $t_p = 1000$ years, ($a_{\text{max}} = 0.34 \, g$), the structure experiences partial or total failure, $(\mu > 2.5)$, which does not comply with the design criteria on seismic safety. In the concrete case, for the design criteria $I$ (without damage), $II$ (linear behaviour with limited nonlinear deformations of individual elements of the system) and $III$ (deep nonlinearity but without thoroughly disturbed stability), return periods of 100, 200 and 1000 years were adopted, i.e., $a_{\text{max}} =$ $0.12 \, g$, $0.20 \, g$ and $0.34 \, g$, respectively.

5.2 Seismic isolation of the church of St. Nikita

Taking into account what has been stated about justification and advantages of seismic isolation of churches of Byzantine type, types of possible systems and selection of corresponding system for seismic isolation, experimental verification of the efficiency of the proposed system for seismic isolation of the St. Nikita church model, as well as definition of criteria and conditions for application of seismic isolation in historic monuments, an attempt has been made to preliminarily design seismic isolation of the St. Nikita church.

Figures 7–8 schematically show the plan and the longitudinal cross-sections of the (hypothetically) base-isolated St. Nikita church structure.

In accordance with the proposed and experimentally verified seismic isolation system, seismic isolation of the St. Nikita Church consists of:

- Reinforced concrete beams below the massive walls and columns;
- Incorporated seismic isolators – laminated rubber elements with steel stoppers;
- Provided space – channels around the isolation for inspection in the course of time.

It is envisaged that a total number of 20 isolators be installed and distributed as shown in Figure 7. Taking into account that the predominant periods of the earthquakes characteristic for this terrain obtained by seismic hazard analysis range between $T = 0.30–0.70$ sec, the main required characteristic of the isolation system is to provide fundamental period of the structure of $T \geq 1.2–1.5$ sec.
Starting from this design conditions, the required bearing capacity and stiffness of the system of 20 isolators can be defined, considering the total weight of the structure of G = 5000 kN:

- Required stiffness
  \[ K_{\text{system}} = (2\pi/T)^2 \times M \geq 90 \text{ kN/cm} \]
- Required bearing capacity
  \[ N_{\text{isola}} = 5000/20 = 250 \text{ kN} \]

The required bearing capacity and stiffness of the seismic isolators, in addition to the characteristics of the built-in materials are the prerequisites for precise definition of the remaining characteristics of the seismic isolators and the steel stopper elements.

Without going into details about the isolation of the St. Nikita church, it should be noted that the construction of the reinforced concrete beams and the incorporation of the seismic isolators should be done in a well planned phase and by using a corresponding and necessary supporting system in order to avoid deformation of the superstructure, i.e., disturbance of its stability. It is also recommended that the installation of the isolators be controlled and supervised by competent professionals (engineers, architect-conservator, archaeologists).

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 General conclusions

- The main principle and aim of the proposed system of seismic isolation is to control the behaviour of the integral structure with all its artistic values in order not to experience any damage during strong earthquakes.
- The seismic isolation system in historic monuments provides protection through restriction of relative and total displacements as well as absorption of the hysteretic energy performed by the stopper-elements.
- The main result of the project is demonstration of the efficiency, as well as technical, economical and conservatory justification of the applied technique of base-isolation on the structure of the church model.
- The results from the experimental investigation point to complete control of the behaviour of the base isolated church model.
- The tests undoubtedly proved that the new technology of seismic base isolation of historic monuments offers absolute safety and protection and that its application should become an imperative in earthquake protection of historic monuments in future.
- Such a scientifically based and verified technology applied in this kind of extraordinarily important structures will enable permanent, efficient and economically justified seismic protection, particularly if one has in mind that the entire intervention takes place solely below the foundation level.
- Imposed as the next phase are analytical investigations of the response of the church model and comparison with experimentally obtained results.

6.2 Recommendations

- To complete this specific investigation, it is important to implement the results in real structures for which conditions have already been created.
- Seismic isolation is successfully applied in compact structures of relatively minor proportions as are the Byzantine churches in Republic of Macedonia.
- In applying seismic isolation in reality, the equipment should obligatorily be tested prior to installation.
- It is also necessary to perform a detailed analysis of the dynamic response of the building structure by corresponding mathematical models and earthquake records.
- Due to the specific nature and importance of historic structures, it is recommended that seismic isolation be performed by professionals and supervised also by persons competent in the field.

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