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AN APPRAISAL OF BASE ISOLATION FOR LARGE MONUMENTAL BUILDINGS

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Abstract. *Traditional techniques for improving the seismic performance of buildings are based either on the increase in strength or in ductility or, sometimes, of both at the same time. This approach, however, can lead to interventions often deemed as too invasive on heritage buildings. An interesting alternative approach consists in the seismic base isolation of this type of buildings. This modern technique acts rather reducing the seismic energy fed into the structure, rather than trying to forcibly increase its strength or its ductility with local reinforcements.*

The aim of this work is related to the appraisal of available base isolation techniques with reference to the application to large monumental buildings, where several peculiar aspects have to be considered due to the building age, the urban context around these buildings, the remains of previous constructions these buildings might have been built over. All aspects complicating choice of the isolation system and the positioning of the isolation plane.

Furthermore, in this work a base isolation intervention exploiting a classical technique of creating the isolation plane is designed and compared with a new proposal that seeks to obtain the isolation plane several meters below the building foundations.

1 INTRODUCTION

Italy is one of the countries characterized by the higher seismic risk in Europe. At the same time is one of the countries with the higher number of historical and monumental buildings.

The Italian stock of historical and monumental buildings consists mainly of masonry structures dating back to centuries ago, or even just at the beginning of the last century. All these buildings can be highly vulnerable to the action of earthquakes, where even moderate-intensity events may cause the collapse or severe damage.

Traditional techniques for improving the seismic performance of buildings are based either on the increase in strength or in ductility or, sometimes, of both at the same time. This approach, however, can lead to interventions deemed generally too invasive on buildings recognized as historical landmarks, and as such preserved with the least amount of visible change. For this reason a less satisfying alternative is accepted in the guidelines, and codes, for such buildings (e.g. the Italian guidelines [1]) since the designer is allowed to settle for the simpler goal of achieving an improvement of the seismic behavior, rather than fulfilling the seismic performance mandated for buildings of new construction. To reach this simpler, and less invasive, goal, the required improvements can be specific and localized. This interventions, however, do not guarantee the survival of the structure and can even be detrimental, causing damage in otherwise non-reinforced parts.

An interesting alternative approach consists in the seismic base isolation of this type of buildings. This modern technique acts rather reducing the seismic energy fed into the structure, than trying to forcibly increase its strength or its ductility with local actions.

The aim of this work is related to the appraisal of available base isolation techniques presented in the literature, with reference to the application to large monumental buildings.

Several peculiar aspects have to be considered when dealing with heritage and monumental buildings (at least in Europe), since due to their age they might have been incorporated in larger built-up units, or they might have been built over previous buildings whose remains can be themselves of interest for the cultural heritage. Further complicating the choice of the isolation system and the positioning of the isolation plane. As a paradigmatic example we will focus in this paper of one of the most widespread typology of heritage buildings in Italy, that is to say on churches, although aware of the high simplification coming from the necessary brevity of this paper. Some considerations on the most suitable (or not) churches typology, built between the 5^{th} and 17^{th} century, will be made focusing on the intent to apply a protective solution founded on base isolation.

2 PRINCIPLES OF BASE ISOLATION SOLUTIONS

The widespread presence of architectural heritage in Italy and the seismic hazard of the area makes the use of base isolation a technique particularly promising in order to preserve the cultural heritage from the damage caused by earthquakes.

As it is well known (e.g. EC8 [2]), the purpose of the isolation system is the reduction of the seismic response of the lateral-force resisting system of the isolated structure. This reduction may be obtained either by decoupling the structure from the ground motion, or by increasing the damping, or by a combination of these effects. Decoupling can be achieved by increasing the fundamental period of the seismically isolated structure (see Fig. 1), or by modifying the shape of the fundamental mode or both. To this decoupling, it follows an increase of the displacements.

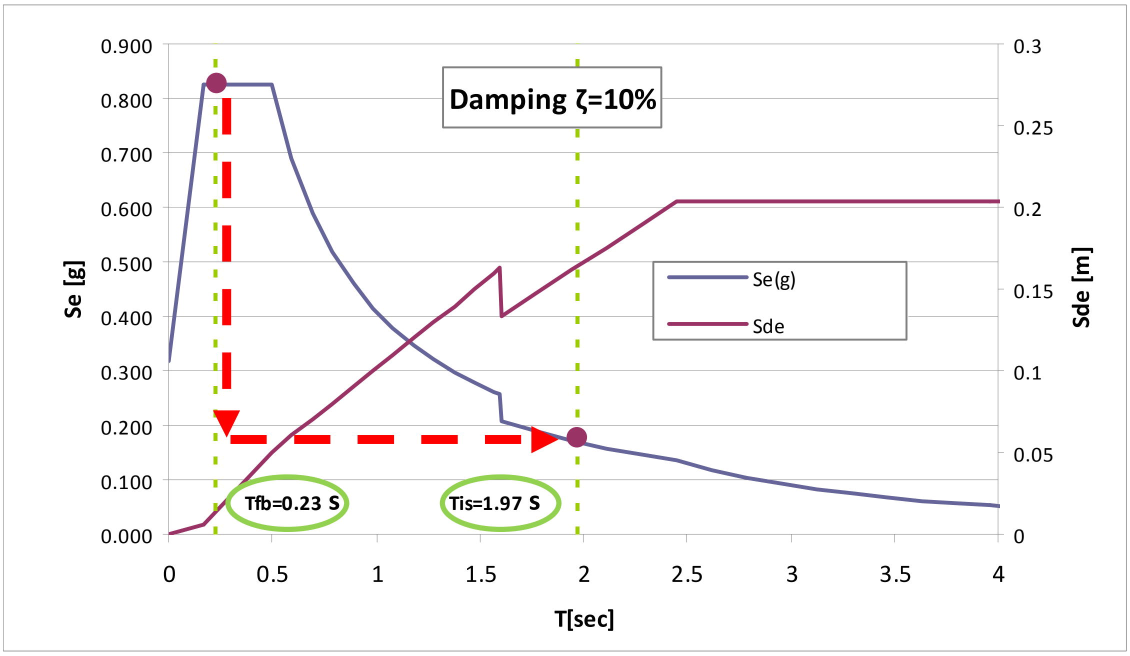

Figure 1: Principle of base isolation.

The isolation system may consist of linear or non-linear springs and/or dampers (isolator units) such as laminated elastomeric bearings, elastic-plastic devices, viscous or friction dampers, friction pendulums, etc., which are generally located below the main mass of the structure. In buildings, the devices providing seismic isolation are frequently arranged on a single interface (the isolation interface) located at the base of the structure, which separates the substructure from the isolated superstructure. The purpose of each isolator unit is to provides one or more of following functions: increased lateral flexibility, vertical–load carrying capability and high vertical rigidity, energy dissipation, recentering capability, sufficient lateral stiffness under non-seismic service lateral loads.

According to EC8, whenever the superstructure remains within the elastic range, in the design seismic situation, it is considered as fully isolated, otherwise the superstructure is assumed as partially isolated. A recent review of base isolation in the Italy and the world can be found (e.g. in [3]).

Besides the properties of the specific devices adopted, a key issue in base isolation is the necessity to create an isolation plane. The purpose of the isolation plane is to effectively decouple the motion of the superstructure from that of the substructure and to control the effects of differential seismic ground motions. In order to achieve the last point, in buildings, presence of a rigid diaphragm above and under the isolation system is required. These rigid diaphragms may be reinforced concrete slabs (e.g. [4]) or grids of RC or steel tie-beams ([4, 5]). The creation of these rigid diaphragms is however one major problem in applying the base isolation technique to existing historical buildings, since it results almost always in invasive, delicate, hand labor prone, activities near or below the foundation level of the building.

In the following some consideration on creating such a plane, and the extension of the same, will be proposed with reference to religion buildings in general, focusing on their characteristics through time with a specific interest in those in Italy.

3 CHURCES AS PARADIGMATIC HERITAGE BUILDINGS

Churches can be assumed as paradigmatic examples of heritage buildings. Focusing on the intent to apply base isolation as a protective solution, in the following, some considerations on churches typology, in between the 5th and 17th century, will be made. Hoping they will be of some value although aware of the possible oversimplification coming from the length of this paper.

In architecture, the period between Late Antiquity (5th century) and Middle Age is characterized by the fusion of Roman, Hellenistic and Oriental cultural traditions; in particular, the typologies of the central plan buildings (church or building that has a design with a primary central space, at times surrounded by symmetrical areas around each side) coming from the *mausoleus* typology, and that of the *basilica*, the Roman building of public life, will be developed and will last for a long time. The large churches of this period were often of the central plan type. As to churches of central plan, that of San Lorenzo in Milan, Italy, is particularly important since it was taken as a model [6] for a further series of central plan churches (Figure 2) all around Europe and Western Asia. The evolution of San Lorenzo, can be taken as paradigmatic as well to illustrate what can be expected from an historical building in urban area. The church of San Lorenzo was built starting from the late 4th century, and heavily modified several times up to the 18th century.

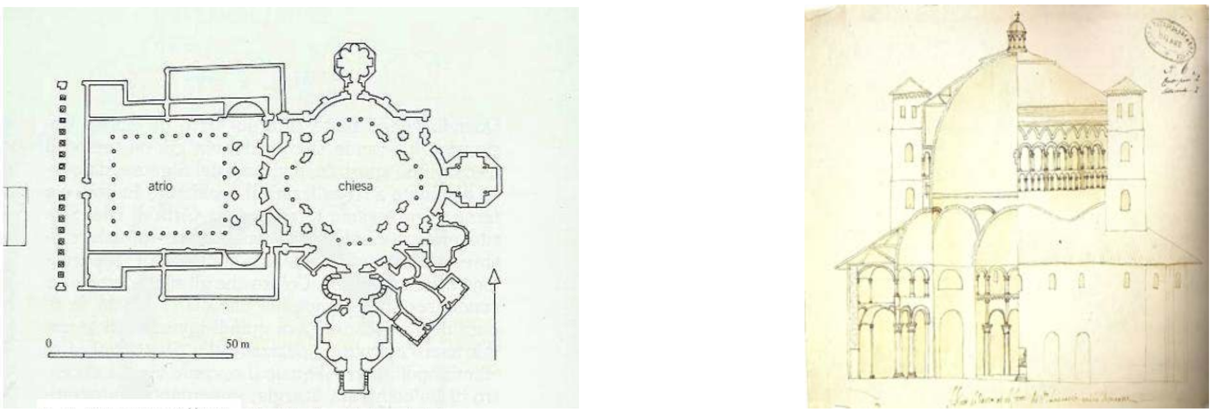

Figure 2: Plan and cross-section façade of the S. Lorenzo church, Milan (Italy). Adapted from [7].

This church typology often presents a curtain of chapels around its perimeter, these were either added in more recent time or built in the original layout. Presence of such chapels makes the roofing system more articulated, with additional ridges, hips and valleys, which in turn lead to a more deformable roof structure. Moreover, besides perimeter chapels, sometimes, in the course of time, even additional buildings were added to the church, as in Figure 3.

A series of interventions occurred to S. Lorenzo church, making the building even more complex: left in Figure 3 is presented the back side of the church as it was at the beginning of the 20th century; right, in Figure 3, the church as it is today.

Figure 3: S. Lorenzo church at the beginning of 20^{th} century (left) and today (right).

The second typology we consider is the *basilica*: the most common church typology from the 9^{th} and 10^{th} century onward.

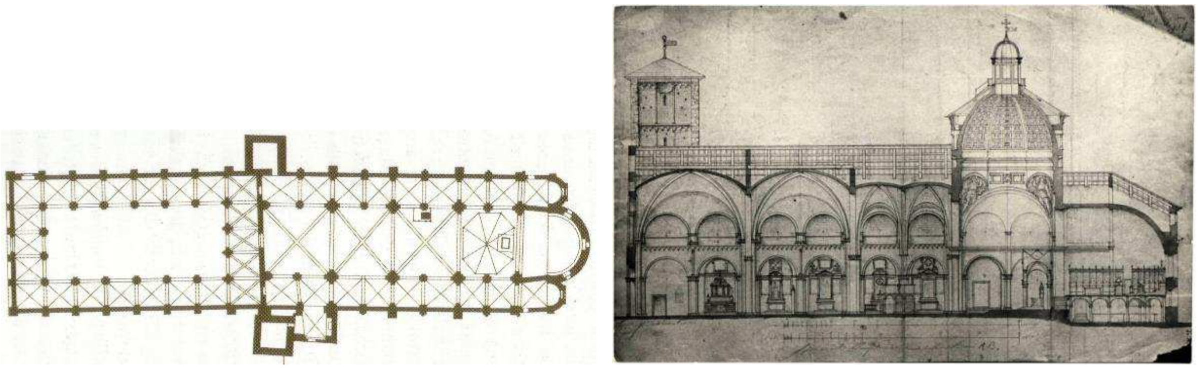

Figure 4: S. Ambrogio basilica, Milan (Italy). Plan and longitudinal cross-section.

As an example, the S. Ambrogio *basilica* built at the end of the 4^{th} century, is represented in Figure 4. A rectangular *portico (porch)* is forward of the church; the plan is divided into three naves, ending with a semi-circular apse. As many others ancient basilicas, S. Ambrogio church is built on a crypt. The present crypt, partially underground, was built later, in the second half of the 10^{th} century, during the restoration works of the apse area. An ancient crypt, however, had already been built in the 4^{th} century.

Presence of a crypt, is commonplace. When a crypt is not present, due to the stratification of constructions in time, often remains of previous buildings, worth of being historic heritage themselves, can be found beneath the foundation levels of ancient churches, since these were often built over existing public or religious roman buildings.

In the 8^{th} and 10^{th} century two bell towers were built on both sides of the *basilica*. Due to the presence of the towers and of a lateral chapel on the right nave the plan is irregular, making the implementation of the technique further more complicated.

Proceeding in time, churches built in Gothic style had thin walls with many windows, and developed more in the vertical direction with respect to the previous Roman style. In order to hold up lateral forces, flying buttress were adopted. In Figure 5 is represented the plan and the back side of the Bourges cathedral. The church was built between 1195 and 1270, in the same place of the previous 11th century cathedral, maintaining the ancient crypt.

In 14th century, due to a structural problem of the south facing tower a flying buttress was added. The north facing tower was built later in 15th century but in 1506 collapsed, demolishing the *façade* gate that was rebuilt.

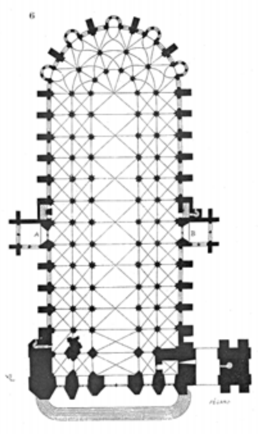

Figure 5: Bourges (France). Plan and back side of the cathedral.

Later in time, in the 17th century, the approach to the construction of monumental buildings changed, since these were often included within the urban fabric. In this period, the façade was supposed to belong to the street, or to the square. The building, built to be admired by people, had to show its importance. The S. Agnese in Agone church (Figure 6), built in Rome between 1652 and 1655 is representative of this philosophy.

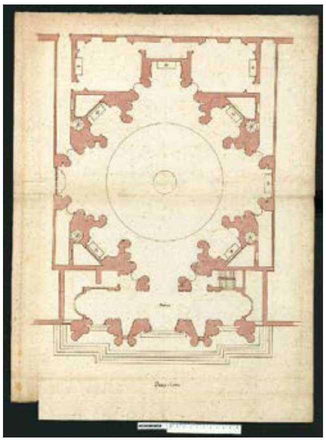

Figure 6: S. Agnese in Agone. Plan and façade on Navona square, Rome (Italy).

4 CONCEPTUAL DESIGN AND SOLUTIONS FROM THE LITERATURE

In the previous sections we have highlighted one of the main issues in adopting a base isolation solution, the practical realization of the isolation plane, and briefly reviewed three representative religious buildings of different epochs. In this section some solution from the literature will be recalled, and some comments on similarities between base isolation of large heritage buildings and other newly constructed based isolated heavy buildings will be offered.

The topic of base isolation of churches has recently received the attention of several researchers, stimulated by the large number of churches that suffered some damage after l'Aquila 2009 earthquake and, more recently, the Emilia 2012 one. The main issues are the creation of the rigid diaphragms above and below the isolation plane and the choice of the devices taking into account also that the positioning of the isolation plane and its construction should be such that the devices can be accessed for maintenance and substitution. The first point can be further separated in operations (insertion of the devices, creation of the diaphragms or tie beams) under perimeter walls and under internal elements of the plan of the building.

Creation of the isolation plane has been addressed in the literature according to three radically different approaches (see, e.g. [8]). The first one, recalls of well known remedial intervention techniques on masonry buildings suffering foundations problems and, as such, is well documented in the literature [9, 10] and accepted by those supervising the interventions. It requires, however, longer time and larger (often by hand) work in restricted spaces.

In this case, the typical construction phases for the realization of a full depth tie-beam system trough the masonry walls are the creation of pockets of small length (1÷3 m) in the masonry walls removing the masonry at the isolation device positions. Each pocket is worked on at a different time, the work is scheduled in such a way that work starts on a new pocket when it has already been finished on the next pocket on the right and on the left. The height of the these pockets should be enough to contain the lower and the upper beam as well as the isolator device. First a lower and an upper Reinforced Concrete (RC) sandwich beam is built on each side of the masonry, and are connected with transversal beams trough the masonry wall over the length of the pocket, the masonry on the pocket is removed for the length necessary to place the device. Then the device is positioned and put under vertical load. The rest of the masonry in pocket is removed and a lower cap-beam and an upper cap-beam is built The sandwich beams, the lower concrete beam and the upper one all have overlap steel bar so that can be connected with the beam portion the next pocket. Furthermore, this technique requires that a basement exists under all the building plan, and can be accessed.

A second technique, internationally patented [4], is based on construction of a new RC mat foundation on the ground. A second RC mat foundation is then built, laying on the first, and connected to the existing foundations or walls of the building. The building is lifted using jacks connected to special devices included in the upper mat foundation, pushing on the lower mat foundation, and isolation devices are pun in place. If the second mat can be connected directly to the existing foundation of the building, no cut of structural elements of the existing building is required. Access holes are formed in the second mat foundation to access and service the isolation devices. This approach requires access to all the area beneath the plan of the building. According to documentation provided by the inventor, building over 22000 kN in weight have been lifted with this technique. At any rate, the weight of what are considered as small basilicas ([11]) is estimated at 170000 kN, with large ones having a weight in the range of 3000000 kN.

The last approach at creating the isolation plane takes a completely different route, working sufficiently below the foundation level [12] so that not to induce a large distress in the stress distribution of the existing building. According to this last technique, named as “Deep Base Isolation” (see Figure 7) special segmental horizontal pipes are inserted below the building, side by side. The pipe's section is peculiar, being composed of two independent halves rigidly connected by removable elements. The diameter of the pipes should be at least 2 m, in order to allow for the positioning and inspection of the isolator units.

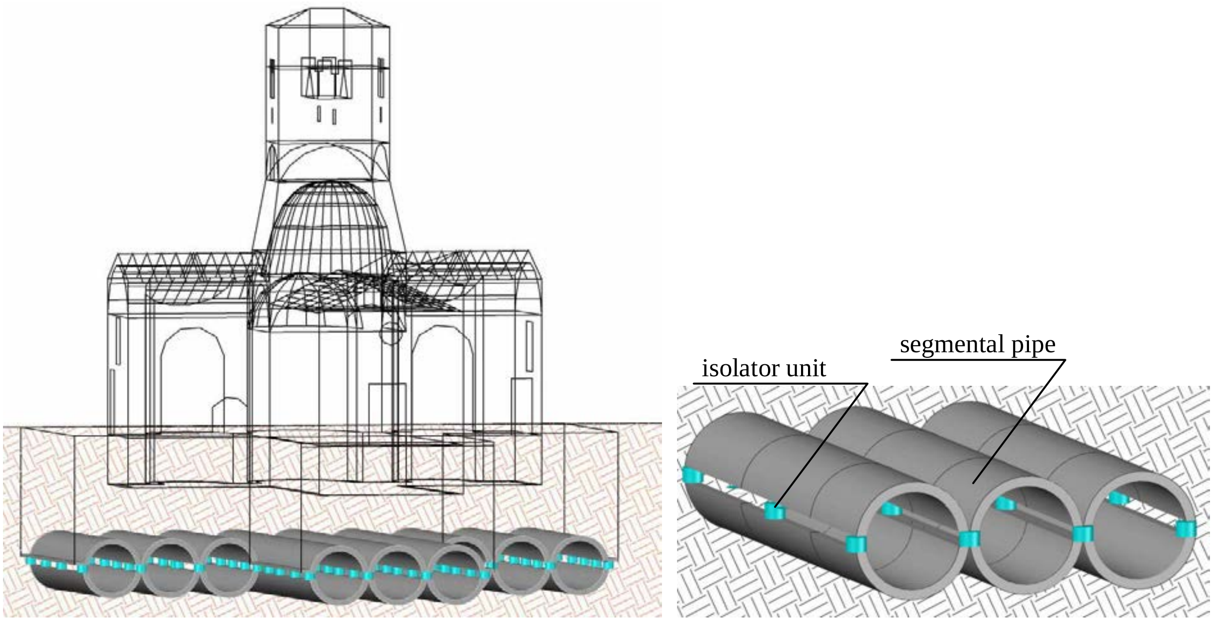

Figure 7: The “Deep Base Isolation” approach in in [12] to create an isolation plane below the building foundations level.

According to the proposals for this technique the building sequence is roughly the following: the pipe segments are first lowered to their final level (it has been suggested a level 4÷6 meters below the building foundations) in a trench dug along one side of the building, and then set in place by means of auger boring or micro-tunneling technique. The isolator units are positioned and the special connection elements between the upper and lower part of the pipe segments, removed. The trench is then completed around the building after having built vertical walls along the four sides of the same, connected to the pipes.

Although no realizations have yet been made with this technique, it nevertheless seems very interesting since the building architectural aspects are not changed, even underground. Accessibility of the isolator units is guaranteed, even for the ones under internal elements. The isolator units need not to be located directly under the vertical element of the building.

This technique has some drawbacks, as well: an additional mass is added to the isolated superstructure, influencing the size of the isolator devices. This mass is in the range of 20% of that (170000 kN) of a small basilica, to 10 % of that (3000000 kN) for a very large one. The weights of the basilicas are taken form data listed in [11].

With relation to the mentioned paradigmatic churches and literature approaches at creating the isolation plane, one can conclude that: for the S. Lorenzo church, the resulting complex intersection of masonry walls make the implementation of the base isolation technique more difficult to apply, but not impossible. Requiring the creation of a larger isolation plane. For the S. Ambrogio example, in order to implement the base isolation technique a deeper isolation plane seems desirable, due to presence of the crypt. Hence, the last technique reported is a suitable candidate. For the S. Agnese church, instead, due to very close proximity with adjacent buildings of ancient age, which can themselves be of heritage importance, the implementation of the base isolation technique seems, at present, not feasible at all.

As a final note, due to the peculiar flexibility of the roofing structure, compared to the perimeter walls, base isolated churches should not be sensitive to rotational effects of the seismic ground motion, which have been evidenced for other base isolated large structures of similar dimensions and mass [13, 14].

5 TENTATIVE APPLICATION TO A PROTOTYPAL CHURCH

The object of a tentative application using a traditional technique and an innovative one is the church depicted in Figure 8. This church was built before the 10th century in North-East Italy near Verona and, given its size, seems an ideal candidate to all the possible techniques for achieving the isolation plane.

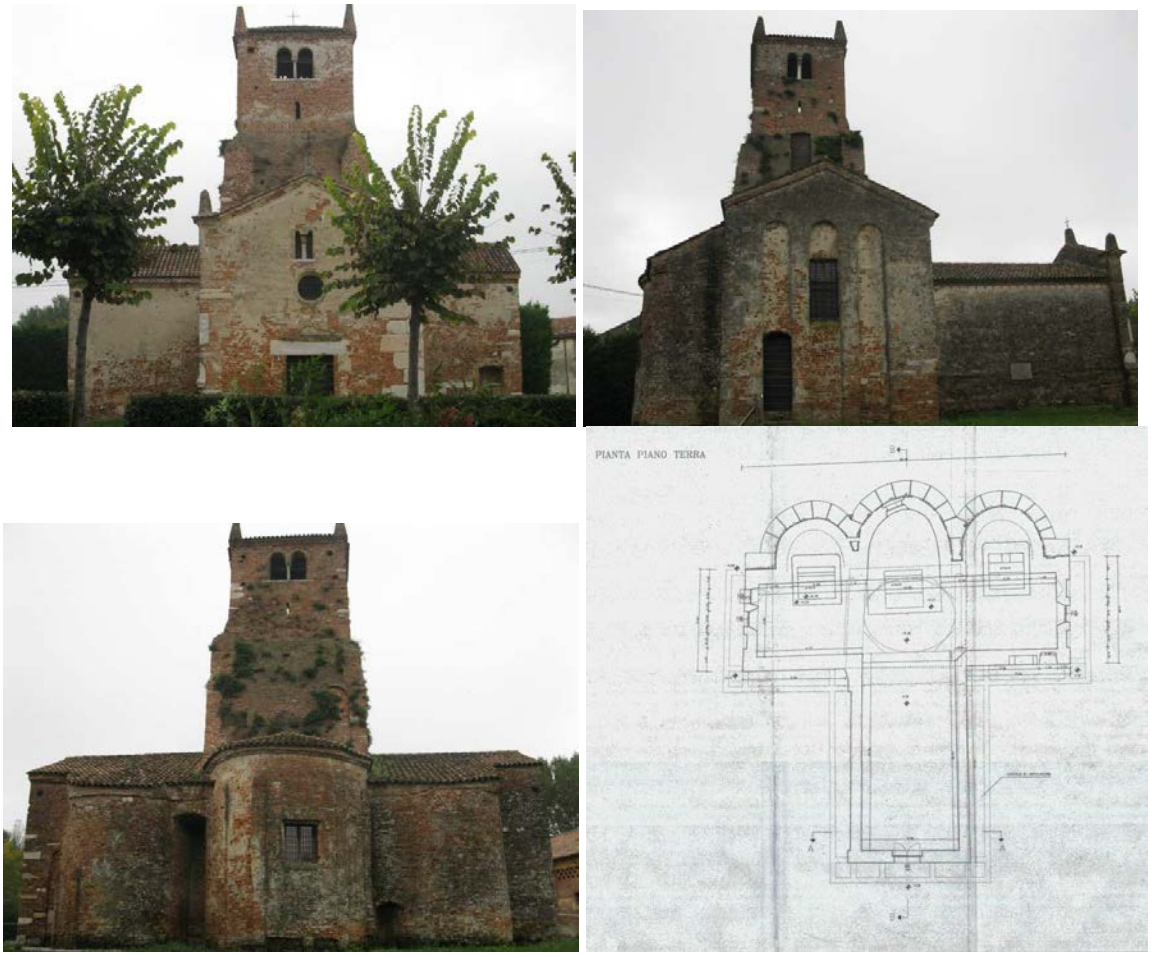

Figure 8: Prototypal church for application of base isolation.

The religious building has a latin cross plan, terminating in a central apse flanked by two smaller apses on the transept open. The church has a single nave with a wooden roof and roof trusses, while the arms of the transept are covered with barrel vaults. At the intersection of the transept with the nave is a taller tower-lantern, which contains inside a dome with elliptical base. The maximum plan dimensions are 20 m in the longitudinal direction and 17.5 m in the transverse direction. In elevation the walls of the transept, nave and the apse have a maximum height of about 6.4 m, while the lantern-tower reaches 16.5m. The masonry thickness varies between 60 and 80 cm, and is characterized by the abundant use of typical red brick from the Verona area.

Figure 9: Nave with the wooden roof and view of the transept.

The structure's behaviour with and without seismic base isolation was studied with the aid of the finite element model in Figure 10. To describe the global behaviour of the church, shell elements are chosen for the walls and beam elements for the beams of the roofs and arches. The following mechanical parameters were adopted throughout the building: modulus of elasticity E = 1500 N/mm^2, shear modulus G = 500 N/mm^2, specific weight of the material w = 18 kN/m^3.

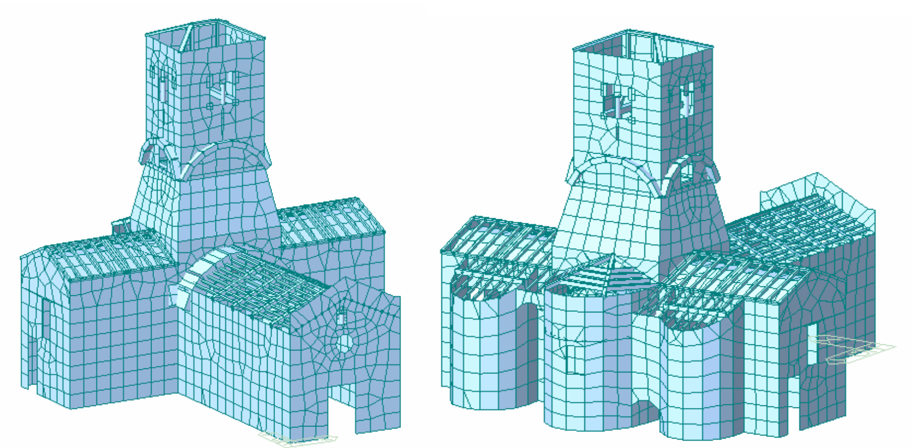

Figure 10: Finite Element model for the proposed application of base isolation.

The first four modal shapes for the church with fix base (having periods 0.2490 s ,0.2204 s, 0.1845 s, 0.1283 s, respectively) are depicted in Figure 11 while Figure 12 shows the participating modal masses (ratio of modal masses to total mass of the church) versus the periods for the first modes in the X and Y directions. X direction is parallel to the transept, Y direction is parallel to the nave.

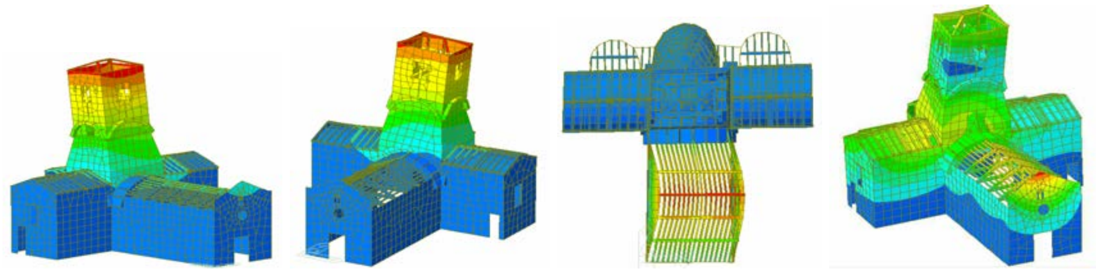

Figure 11: First four modal shapes (periods are 0.2490 s ,0.2204 s, 0.1845 s, 0.1283 s, respectively).

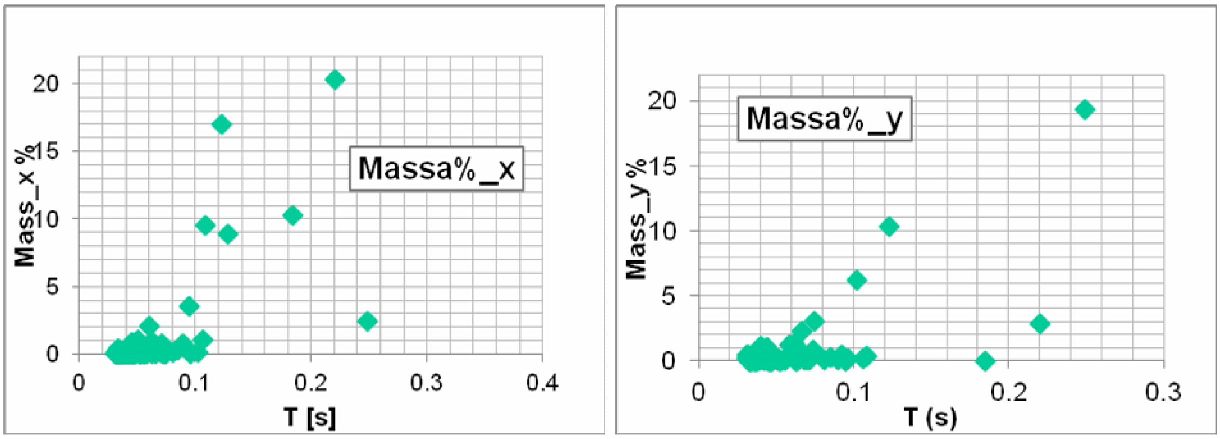

Figure 12: Participating *X* and *Y* modal mass vs. mode periods.

For the purposes of this work the church was analyzed under a Peak Ground Acceleration (PGA) value a_g = 0.172 g at he Live Safety Level defined in [15], larger than the one prescribed by the Italian a-seismic code at the site of the building. The value of the soil amplification coefficient in the analyses was S =1.5 and the behavior factor was q = 2.25. Under this value of the PGA and with the listed values of the other parameters defining the seismic input the church demonstrated vulnerability for some local mechanism of collapse, depicted in Figures 13 and 14, primarily related to typology of the roof which has no bracing in the roof plane to stabilize the out-of-plane motion of the nave walls.

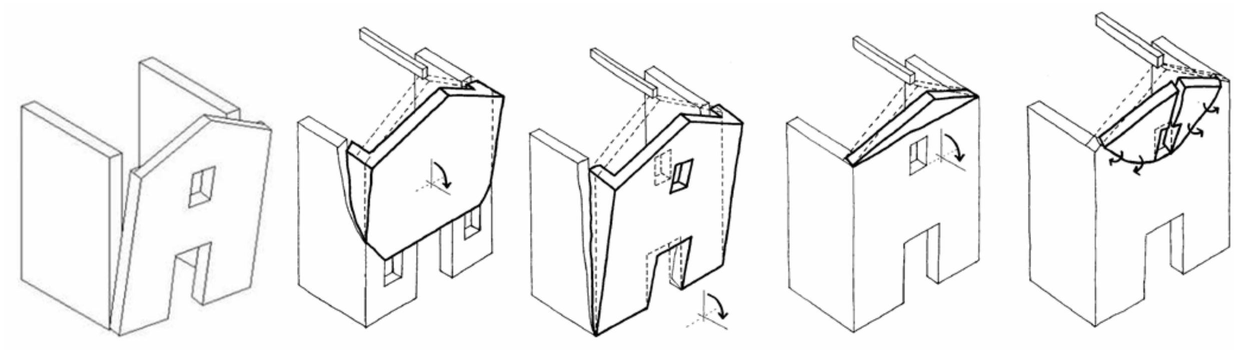

Figure 13: Possible mechanisms of collapse for the principle face and for transept's ones.

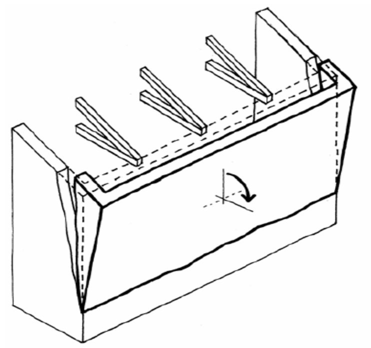

Figure 14: Possible mechanisms of collapse for nave and lateral walls of transept.

6 BASE ISOLATION OF THE PROTOTYPAL CHURCH

As a remedial measure to the deficiencies described in the previous section, two isolation systems were designed. The first is of the classic type for realization of the isolation plane since two rigid diaphragms identify the isolation plane. This marked by solid Reinforced Concrete (RC) slabs of 30 cm thickness. Upper and lower RC cap beams connect the isolation devices and support the perimeter walls. In this design the isolation system is designed for a target period of the isolated superstructure T_{is} = 2 s which is greater than three times that of the building with fix base, as prescribed by the Italian code [15]. The mass of the isolated superstructure, including that of the RC diaphragm and of additional tie beams, is 1272 kNs^2/m. One isolator every 2.5 m along the perimeter walls is assumed so that the cap beams are not too slender and strains in the perimeter walls is sufficiently small.

A first tentative, using only High Damping Rubber Bearing (HDRB), led to devices of small diameters, unfit to carry the vertical loads. Lead Rubber Bearing (LRB) were not considered due to the stiffness being to high. The final configuration comprises 19 HDRB devices with diameter D = 400 mm, having K_e = 0.52 kN/mm, and 5 with D = 450 mm, with K_e = 0.61 kN/mm. These are supplemented by 8 slider devices, as depicted in Figure 15. The damping ratio is 10% of the critical one.

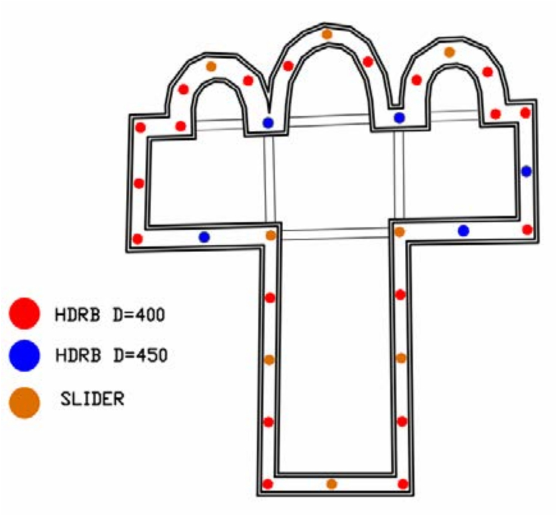

Figure 15: Final configuration of the devices for base isolation of the prototypal church.

This solution allows for a sensible reduction of the relative displacement of the walls crown with respect to the isolation plane. It gives, however, in only a mall decrement (30%) of the base shear with respect to the fix base structure. This is due to the dispersion of the mass over several modes of similar period and by use of the Complete Quadratic Combination to estimate the base shear. Besides the isolated period of 2 s is not sufficient to achieve an acceptable reduction factor of the base shear even if a larger mass would have participated in the first modes.

The second isolation system designed as a remedial measure is of the "Deep Base Isolation" type described in [12], using pipe segments located 4 m below the church's foundations. Considering that the selected church was built over a smaller preexisting chapel, this approach to base isolation is of value assuming that remains below the church plan are to be preserved. Given that the plan of the church is cross-shaped, the deep isolation plane can be achieved with different extensions of the pipe segments, as shown in Figure 16. Consideration on the length of trench required to lower and position the pipe segments, and on diffusion in the soil of the stresses induced by the foundations, lead to select the solution in Figure 16-center. Preliminary computation lead to a total weight of 77676 kN for the superstructure plus the soil layer. The corresponding mass associate to a target value of the isolated structure period of T_{is} = 3.0 s, leads to selecting 42 HDRB devices D = 550 mm and 6 devices D = 600 mm, plus sliders as depicted in Figure 17.

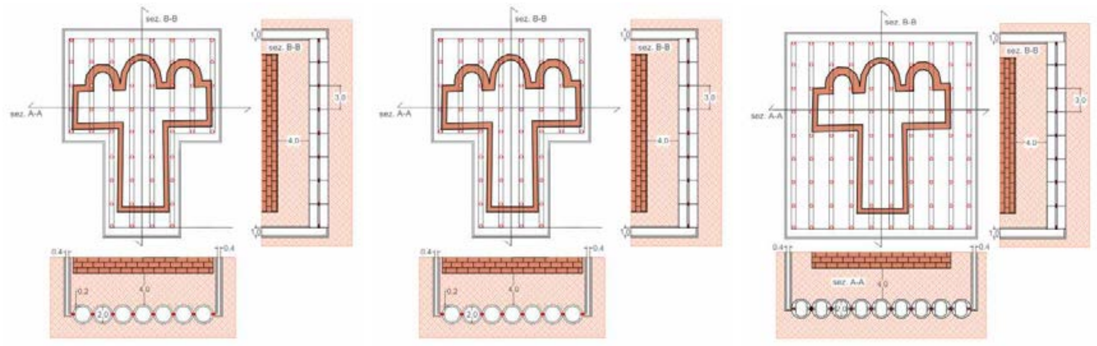

Figure 16: Possible applications of the technique in [12] to a prototypal cross-shaped church.

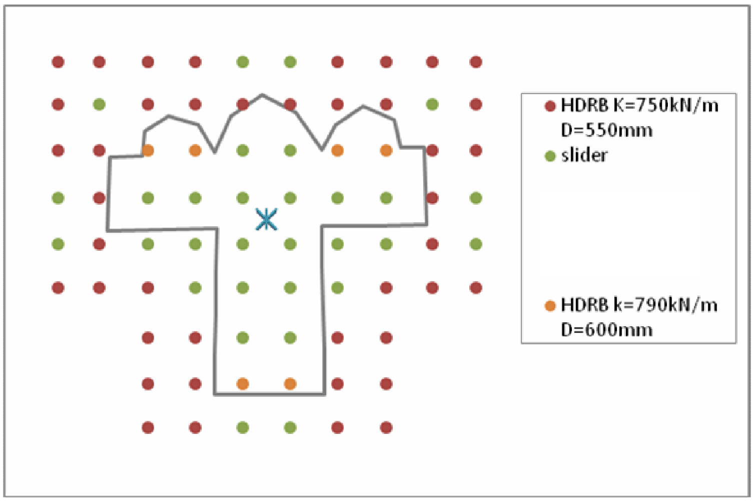

Figure 17: Final configuration of the devices stemming from the technique in [12] applied to the prototypal cross-shaped church.

This last approach to base isolation leads to a 70% reduction of the base shear with respect to that of the fix base structure, and to the preservation of the original floor and of the remains below the same. However, by comparing the sheer costs of the HDRB devices, this solution implies more than three times the cost with respect to the first isolation solution. This is due to the fact the isolated mass is six time that mass of the church alone, and that this aspect increase the number and the dimension of the devices.

7 CONCLUSIONS

Seismic protection interventions on monumental buildings often have to undergo severe limitations, due to the rules in force for the protection of the monumental heritage. This applies, in particular, to the case of churches, the majority of which were built without any consideration of seismic actions. In this situation, the recourse to the base isolation technique is of special interest in all cases when the church complex is not connected to other buildings.

As discussed in this work, special solutions have to be identified in relation to the peculiarities of the problem of churches. Two main aspects are determinant in the choice of a suitable base isolation system: interventions on existing walls should be avoided and the possible presence of remains under the church should be considered. All these aspects lead to the adoption of a solution based on an isolating sliding surface at some depth under the church foundations. In this sense, the technique based on a series of parallel tunnels, as presented in the paper, although never applied in practice, looks promising. In this respect, further and more detailed studies are needed to reliably define all the details involved in such an ambitious and complex work.

Interestingly, a similar solution, i.e., the adoption of a double foundation mat with isolating devices interposed, is suitable for both new industrial plants and old churches as well; in the latter case, however, the need of acting below an existing structure and avoiding differential settlements results in a more complex construction and in additional costs.

As in the case of an industrial facility, the total mass resting on the isolation system may be considerable, mainly if the system has to be installed at some depth. In the case of a church, however, the isolated structure is flexible; for this, the rocking effect, which is typical of the rigid body behavior, does not need to be considered.

As discussed in the paper, the church layout may be very different in relation to the construction period; as a consequence, the design of an isolation system may lead to very different solutions and, some times, to unacceptable costs.

The comparison of designs, for a prototypal cross-shaped church, carried out suggests that classical techniques of realizing the isolation plane lead to smaller devices and hence to lesser costs in terms of sheer cost of the devices.

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