Simon PETROVČIČ
David KOREN
Vojko KILAR

Applicability of base isolation made of elastomeric isolators for the protection of cultural heritage

This article briefly presents the applicability of base isolation made of elastomeric isolators for the protection of heritage architecture. The first part of the article gives an illustrative overview on the use of base isolation throughout the world, together with an analysis of guidelines for the protection and management of places of heritage architecture. The guidelines which are given through international agreements and resolutions on the conservation of monuments have to be considered when designing the base isolation of existing monuments. Generally, interventions into such structures should be minimal or visible as little as possible and should minimally affect the aesthetics and functionality of the object. In the second part of the article the general and some special requirements for base isolation design with elastomeric isolators are presented. The influence of the slenderness of the structure is analysed in more detail. The analysis is based on the corresponding rocking prevention criterion, upon the condition that the isolators cannot bear any tensile forces. The article concludes with a presentation of the maximum height-to-width ratios for objects that can be mounted on isolators, fulfilling the given rocking prevention criterion for different soil conditions. The maximum aspect ratios have also been determined by considering 5 appropriately scaled ground motions from the 1998 Posočje earthquake.

Key words: cultural heritage, architectural monuments, base isolation, elastomeric isolators, earthquake safety, measures for increasing earthquake safety

1 Introduction

Increasing the seismic safety of existing objects demands a relatively extensive intervention upon the object itself, therefore such remedial action on existing residential and business buildings is taken only if it is absolutely necessary. The situation is completely different with buildings of special significance, which have for example, a high financial or cultural value. The latter group includes mainly cultural heritage objects, where using also more expensive technological solutions for protection against earthquakes is of no consequence. In the context of this article, the notion of 'cultural heritage' comprises architectural heritage objects, namely cultural monuments, which in addition to their practical and functional value also display special cultural and historical characteristics (Fister, 1979).

Increased seismic safety can be achieved by inserting special elastomeric isolators, which are usually installed at the foundation level of a structure. The main function of base isolation is to increase the period of vibration of a structure or to reduce the level of forces applied to a structure during seismic loading. The experiences gained in recent earthquakes shows that isolated buildings actually behave in accordance with expectations, and successfully reduce the damage caused by earthquakes (Naeim and Kelly, 1999).

Remedial action on architectural heritage objects is, due to their high cultural value, usually extremely demanding. According to the Burra Charter (ICOMOS, 1999), places of cultural heritage need to be protected and should not be exposed to dangers or be left unprotected. Interventions upon such objects should be with minimal or visible effects and should minimally affect the aesthetics and functionality of the object. It is desired that for reconstruction purposes, the same materials as those already installed are used as much as possible. Such materials often do not meet the requirements for mechanical resistance like more modern materials do, and therefore do not significantly contribute to a significant increase in earthquake safety. Frequently with older objects, the design itself is unfavourable from a seismic safety point of view. In this respect, seismic isolation presents a unique solution, as it enables and allows for greater seismic safety of architectural heritage objects with the minimal amount of intervention upon the object itself.

This article briefly presents the use of base isolation made of elastomeric isolators. In the first part of the article some examples of base isolated objects of heritage architecture are given, as well as conservation guidelines that have to be followed when designing base isolation for the protection of architectural heritage. The second part of the article presents the basic guidelines of base isolation design, together with a detailed analysis of the special requirements that affect the design process. The effect of the slenderness of the object (its height-to-width aspect ratio) on the selection of proper isolators is presented. The analysis is based on the rocking prevention criterion upon the condition that the isolators cannot bear any tensile forces.

2 Use of base isolation systems

Bearings extend the structure's vibration period and reduce the forces to the structure induced by an earthquake. In practice, restoration measures on existing buildings make use of the so-called hybrid systems, which in combination with special dampers for seismic energy dissipation enhance the damping capabilities of a structure, and so reduce the level of seismic forces to the structure (Naeim and Kelly, 1999). The implementation of such system is presented in Figure 1. We have to realize that the installation and design of seismic isolation has its particularities and is a unique task with respect to every project. It requires experienced designers and contractors, since misdesigned and misinstalled seismic isolation can in some cases even worsen an object's response to seismic loading (Skinner et al., 1993; Naeim and Kelly, 1999; Kilar and Koren, 2007).

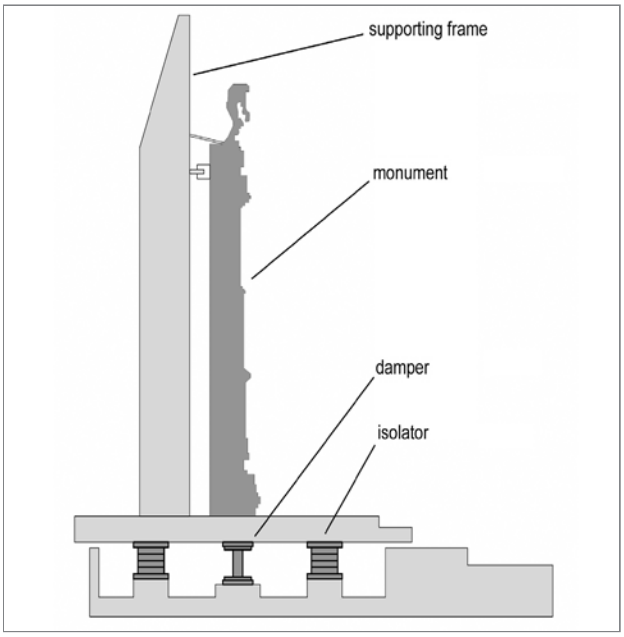

Figure 1: Rodin's Gates of Hell isolated by bearings and dampers (source: Internet 1).

In existing objects, seismic isolation presents a very efficient method of ensuring greater earthquake safety, as the intervention upon the object itself is minimal. This is especially relevant with architectural heritage objects with a high cultural value. In continuation, a few examples of seismically isolated architectural heritage objects will be presented. In Italy, many remedial measures for increasing the seismic safety of architectural heritage objects have been taken (Martelli and Forni, 1998, 2004; Indirli et al., 2006). Besides increasing seismic resistance, restoration using seismic isolation can as well increase the stability of a structure. Such examples are the Cathedral of San Feliciano in Foligno, which also suffered serious damage during the earthquakes in Marche and Umbria and was later appropriately restored using seismic isolation (Martelli and Forni, 2004).

Seismic isolation is becoming more widely used also for the protection of other cultural monuments, such as statues, triumphal arches, obelisks and other similar objects of high cultural value. As an example, we mention the seismic isolation of Praxiteles' statue of Hermes (Figures 2 and 3) at the Olympia museum in Greece, which was isolated by elastomeric bearings (Koumousis, 2007). According to Indirli et al. (2006) and Koumousis (2007), a similar method was used to isolate Rodin's 'The Gates of Hell' at the National Museum of Western Art in Tokyo (Figure 1), the statue of Aphrodite at the Guggenheim museum in New York, the Fountain of Neptune in Messina in Italy, and a number of exhibits in the J. Paul Getty Museum in Los Angeles. Also in Slovenia, which is situated in an earthquake prone area, there are a number of cultural monuments, such as statues, chapels and other objects, where earthquake resistance could be increased in this fashion if necessary.

Figure 2: Installation of seismic isolation for the statue of Hermes at the Olympia museum (source: Koumousis, 2007).

3 Guidelines for the protection of heritage architecture

The Australian National Committee of ICOMOS adopted the Burra Charter in Burra in the South of Australia in 1979 (ICOMOS, 1999). It provides the guidelines for the preservation and management of architectural heritage. The charter is based upon the knowledge and experience of Australia ICOMOS members, as well as on the International Charter for the Conservation and Restoration of Cultural Monuments and Sites (ratified in Venice, in 1964) and the Resolutions

Figure 3: Placing the statue onto seismic isolation (source: Koumousis, 2007).

of the 5th General Assembly of the International Council on Monuments and Sites (ICOMOS) (ratified in Moscow, in 1978). Currently applicable is the revised version dating from November 1999. As indicated by Zupančič et al. (2007), one of the main advantages of this charter is its wide applicability, as it clearly defines the notions, principles and procedures for cultural heritage preservation.

The essence of preservation is defined in the Burra Charter as the "conservation of places of cultural heritage". In this article, a place of cultural heritage presents buildings, monuments, chapels and other similar objects and also comprises of their component parts, contents and premises. The Charter states that any changes to such places are only allowed to the smallest possible extent and that priority should be given to the use of traditional techniques and materials.

Generally any work on architectural heritage objects in order to increase seismic safety should be such, that it least disturbs the aesthetics and functionality of the objects themselves. There is a tendency that with such work we try to find a compromise between achieving a sufficient level of earthquake safety and the least possible disturbance to the original object (Amerighi et al., 2007). The methods of achieving such a harmonious performance, including building techniques, establishing earthquake threats, collapse mechanisms and remedial measures are based mainly on experience from past restoration projects. The UNESCO organization co-operated with the ICOMOS to develop the guidelines that present the expertise that restoration professionals must possess in order to properly plan and commence the renovation of an architectural monument. Zupančič (2007) gives an overview of all of the 14 guidelines, where special emphasis is given with regard to the structural restoration of architectural heritage, of which base isolation could be an integral part.

Guidelines f) and j) are especially important when planning any renovation with seismic isolation. Guideline f) uses the diagnosis of intrinsic and extrinsic causes of decay as the starting point for determining the appropriate action to be taken. Guideline j) recommends additional specialist research into materials technology and static systems. The two guidelines serve as the basis for determining the level of earthquake threat to the object in question, and to prepare a plan for the objects seismic renovation.

Indirli et al. (2006) give proposals on how and to what extent objects of architectural heritage can be interfered with during the process of renovation itself. Their proposals can be summarized in the following points:

1. Deviations from the regulations and criteria applicable to new buildings are acceptable, since these objects are normally not made of modern building materials, such as reinforced concrete and steel, and their renovation is demanding.
2. In regulations that consider objects according to the "limit state" theory of (for example the Eurocode standards), the importance factor can be calculated separately for an individual object.
3. The effectiveness of any improvements should be continuously evaluated.
4. Detailed preliminary studies are recommended.
5. The use of special procedures prepared separately for each individual object undergoing renovation is recommended, since the use of standard procedures is often impossible in such renovations.
6. It is recommended to follow the unwritten principles of construction, which are based on experience.
7. The use of advanced materials can significantly increase the level of seismic safety of an object; however the use of such materials should not disrupt the object's aesthetics and should be compatible with the materials already installed within the object.

4 General requirements for designing elastomeric isolators

The design of base isolation of a building is relatively demanding, as we are dealing with a dynamic system, in which the stiffness of the upper as well as the lower structure plays an important role. An inadequately designed system can do more damage than good if it moves the structure's vibration period to replicate the prevailing seismic periods of an earthquake, thus causing a resonance response.

General requirements which have to be fulfilled when designing base isolation systems are presented in the European regulation on designing earthquake resistant structures – Eurocode 8 (CEN, 2004). The requirements are described in detail and explained also in various scientific publications like Skinner et al. (1993), Kelly (1997), Naeim and Kelly (1999), Komodromos (2000) and Christopoulos and Filiatrault (2006). Some of the requirements that are important for the base isolation of heritage architecture will be summarized in the following paragraphs.

The compliance of general requirements requires 1) a check of the ultimate limit state, which is associated with a collapse or with other forms of structural failure, which may endanger the safety of people and 2) a check of the serviceability limit state, which is associated with damage occurrence, corresponding to states beyond which specified service requirements are no longer met. In both cases the strength and maximum deformability of isolation devices must not be exceeded. The isolation devices must also possess additional safety, which is introduced by magnifying the obtained seismic displacement of each isolator by 20%.

Moreover, the code also requires that every bearing can withstand vertical loading and has the capability to dissipate energy, and to return to its original position, as well as to possess sufficient elastic stiffness to withstand horizontal loading of a non-seismic origin (e.g. the wind). It is important that an isolated structure is separated enough from the surrounding soil and other structures, so that it can move freely in all horizontal directions during an earthquake. To minimize the effects of torsion, it is suggested that the centres of effective stiffness and isolation system damping are as close as possible to the point of projection of the mass centre with regard to the isolation surface. Compression stresses created in isolators due to constant influences should be as even as possible, since in this way, the differences in the behaviour of isolation systems are diminished. Bearings have to be fixed to the superstructure and lower structure. This is achieved by installing a rigid structure above and below the isolation system, for example a rigid diaphragm consisting of a reinforced concrete slab or a grid of tie-beams, designed and taking into account all possible local and global modes of buckling.

When examining the lower structure, it is necessary to consider the inertia forces affecting it directly and the forces and the moments transmitted to it through the isolation system. Several design seismic states including maximal vertical and horizontal seismic load should be considered. The limit state of an isolation system can also be checked with the total drift between the lower and upper side of the isolators, where we should take into account the deformation due to the design seismic action and the effects of shrinkage, creep, temperature and other loading characteristics.

The choice of a suitable seismic isolation system is affected by several mutually exclusive factors. For example, the use of a certain isolation system on the one hand reduces the total horizontal seismic force, but on the other hand, increases displacements of the isolation system. An efficiently designed base isolation system significantly reduces the horizontal seismic force acting on the superstructure, without exceeding the target displacement. The target displacement is determined by considering the mechanical properties of isolators and other requirements concerning the proper width of the dilatations. Therefore, the selection of a final isolation system depends on the total horizontal force created during seismic loading as well as on the horizontal displacement of the isolation system, the importance of the object and the available financial resources.

The effectiveness of a base isolation system also greatly depends on the "slenderness" of the structure, i.e. its height-to-width aspect ratio (Li and Wu, 2006; Egidio and Contento, 2008; Hino et al., 2008). Very slender structures are prone to develop a rocking phenomenon, which is caused by earthquake forces and liftoff of the superstructure, which might eventually lead to the collapse of the entire structure. Hino et al. (2008) present two criteria which govern the maximum allowable slenderness of a base isolated object:

- The ultimate state of tensile strength and liftoff prevention;
- The limit value of the compressive force in the isolators during rocking.

Horizontal and vertical earthquake ground motions have to be considered simultaneously. Elastomeric isolators usually possess very small tensile strength and develop relatively large strains during tensile loading (Skinner et al., 1993; Kelly, 1997). Tension stresses cause a set of small cavities within the bearing rubber, which grow progressively under cyclical loading. This significantly reduces the vertical stiffness of the isolators (Skinner et al., 1993). Numerous authors, e.g. Skinner et al. (1993), Kelly (1997), Li and Wu (2006), therefore suggest that the tension strength of elastomeric isolators should not be considered, and that the isolators should be designed as they can not withstand any tensional force. These special requirements that determine the maximum allowable slenderness of a base isolated object will be further presented in this article.

5 Special requirements for designing elastomeric bearings

5.1 Rocking and liftoff prevention

One of the limit state criteria that determine the characteristics of elastomeric isolators is the rocking prevention criterion, which is based on the condition that the isolators cannot bare any tensile forces (liftoff prevention). If rocking is not prevented, the disconnection of the isolators from the superstructure may occur, which can eventually lead to the collapse of the entire structure (Li in Wu, 2006). As it will be shown, one of the main parameters that determine this criterion is the so called "slenderness" of the object.

Figure 4 presents a base isolation system of a superstructure, with height *H* and width *B* and with *n* rows of identical elastomeric isolators. It is assumed that the isolators are uniformly distributed throughout the layout, in an orthogonal grid and

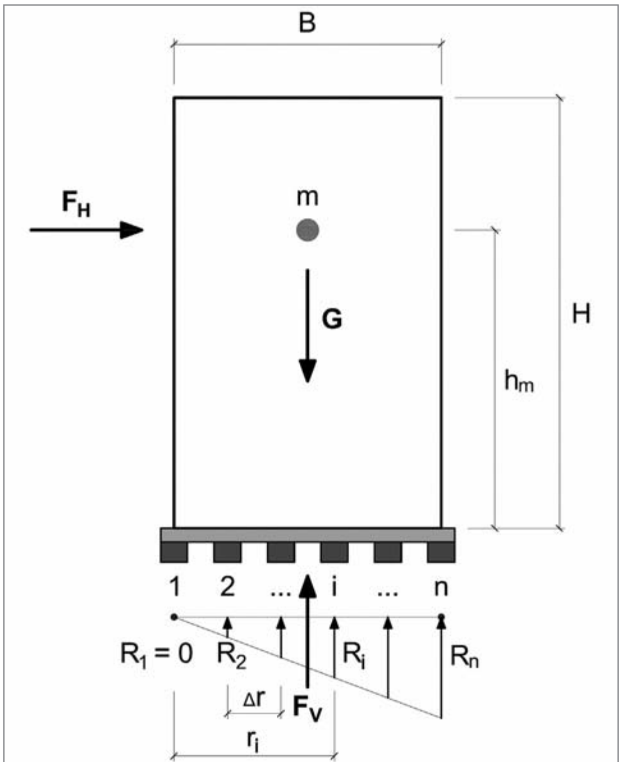

Figure 4: External forces and base reactions of a base isolated rigid body just before entering the rocking phase.

that the distance between the rows is constant. We have assumed that the superstructure is a rigid body, which moves on the isolation system in a horizontal and/or a vertical direction. We believe that the given assumption is reasonable for architectural heritage buildings, which are usually very rigid, but cannot withstand much tensile stress within the elastic range. The centre of mass, which accounts for the mass of the superstructure and the mass of the base isolation system, is located on height h_m.

Forces acting on the system are the horizontal earthquake force F_H, the vertical earthquake force F_V and the weight G. The maximum slenderness (H/B aspect ratio) has been determined on the condition, that the isolators cannot bare any tensile forces. Figure 4 shows the base isolated system just before it enters the rocking phase; when the base reaction R_1 in the first row of isolators is zero and all other reactions (R_2 to R_n) are producing compressive stresses in the isolators. The rocking prevention criterion can be written as the moment equilibrium condition on the first row of isolators. As the distance between the rows of isolators is constant, we can express the vertical reactions and their lever arms as the quotient of the maximum base reaction R_n, with respect to width B and the number of rows of isolators, n. The complete derivation of the condition for any number of rows n is complicated and it is therefore not presented herein. Only the final expression for the normalized slenderness ratio H/B, denoted with λ, is given:

$$\lambda \equiv k_m \cdot k_n \cdot \frac{H}{B} = \frac{1}{2} \cdot \frac{G - F_V}{F_H} \quad ; \quad k_m = \frac{h_m}{H} \quad ; \quad k_n = 3 - \frac{6}{n+1}$$

We can see that the normalized slenderness l is a function of the vertical earthquake force F_V, the horizontal earthquake force F_H, the weight G. Coefficients k_m and k_n represent the effect of the mass height and the effect of the number of isolators, respectively. The coefficient k_m has the range from 0 to 1, while coefficient k_n has the range from 1 to 3. If we have only 2 rows of isolators ($n = 2$), then coefficient k_n equals 1, while by increasing the number of rows the value of k_n converges towards 3. Coefficient k_n with respect to the number of rows of isolators n is depicted on the Figure 5.

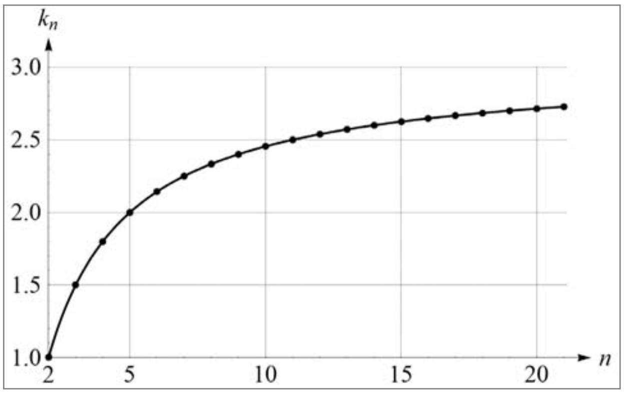

Figure 5: Coefficient kn with respect to the number of rows of isolators *n*.

The normalized slenderness λ presents the normalized limit H/B aspect ratio of a base isolated rigid body in which the combination of horizontal and vertical forces do not cause any tensile stresses or rocking in the elastomeric isolators. The actual limit H/B aspect ratio is normalized with coefficients k_m and k_n. If both coefficients equal 1 ($h_m = H$ and $n = 2$), than the normalized slenderness λ represents the actual aspect ratio H/B.

5.2 Limitation of the compressive force in the isolators

As long as only the vertical loading acts on the system, the compression force in each isolator depends only on the number and arrangement of the isolators. In the case of simultaneous loading in a vertical and a horizontal direction, the base reactions on one side of the object grow bigger than on the other side. Just before the rocking occurs (Figure 4) the base reaction on one side becomes equal to zero, while on the other side the base reaction is much bigger, if compared to the situation when only vertical loading were acting on the structure. It can be expressed as:

$$R_n = \frac{4 \cdot F_H \cdot \lambda}{n}$$

For a given normalized slenderness λ, selected number of rows n and actual maximum horizontal seismic force F_H, the reaction R_n presents the maximum compressive force that occurs in the compressed edge row of isolators. This is an additional design condition, which determines the required compressive strength of the isolators and has to be considered when designing elastomeric isolators.

6 Calculation of maximum allowable normalized slenderness

6.1 Calculation of maximum normalized slenderness with response spectra

In a response spectrum analysis the forces F_V and F_H can be expressed as a product of mass and the horizontal or vertical response acceleration. The response accelerations are obtained from the elastic response spectra given in Eurocode 8 (CEN, 2004) for a given vertical and horizontal vibration period T_V and T. Horizontal and vertical vibration periods are generally not of equal duration. Komodromos (2000) reports that the vertical frequencies of elastomeric bearings are usually between the range of 8 and 12 Hz, which corresponds to the vertical period of about 0.1 s. We have assumed that the vertical vibration period is always in the plateau of the vertical response spectrum. Eurocode 8 also demands that the horizontal and vertical ground components are to be considered 100% in one direction, and 30% in the other direction. All considered quantities are functions of the design ground acceleration $a_g(g)$, ground type and damping of the isolators. By considering the most unfavourable condition, which yields the maximum allowable slenderness for a given vibration period T, we have determined the normalized slenderness λ (Figure 6) for three ground conditions – hard ground, medium ground and soft ground. For each ground classification, the starting periods correspond to the limit of the plateau of the horizontal response spectrum. They equal 0.4 s for hard ground, 0.5 s for medium ground, and 0.8 s for soft ground. The ground types correspond to subsoil classes A, B and D from Eurocode 8. A 10% viscous damping ratio has been considered in this analysis.

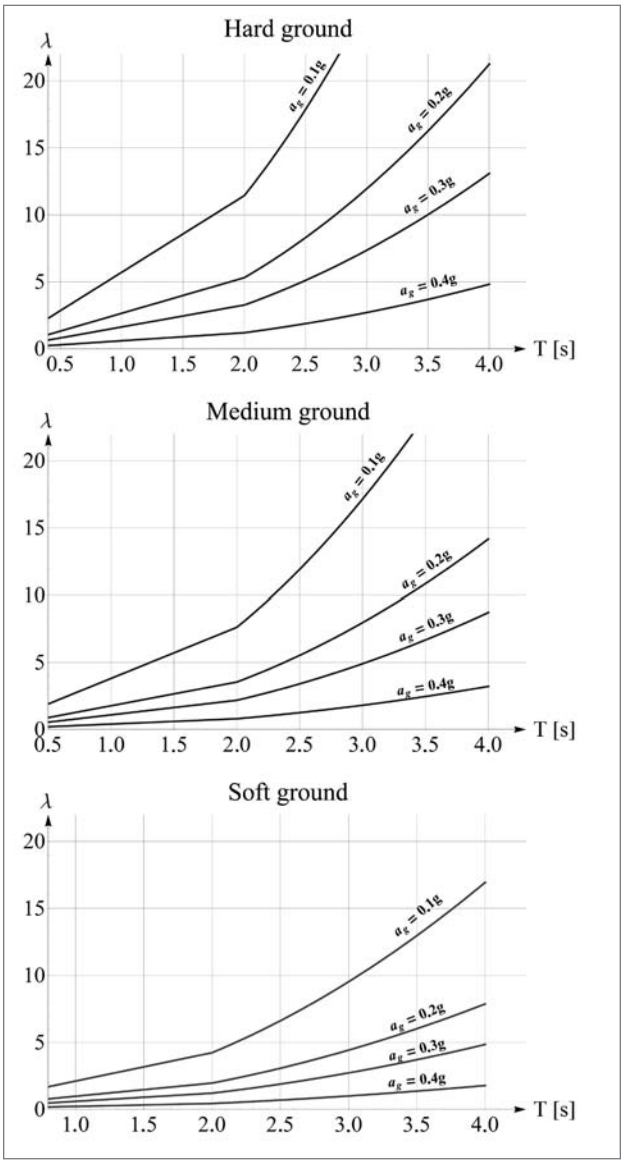

Figure 6: Normalized slenderness λ with respect to the horizontal vibration period for the three different ground conditions.

We can see that the ground conditions have a big influence on normalized slenderness. For example, for the same vibration period, the maximum allowable normalized slenderness can be up to 50% greater on hard ground as that of soft ground.

6.2 Calculation of maximum normalized slenderness with dynamic analysis

In a dynamic time-history analysis, the accelerations and forces F_H and F_V are functions of time t. These forces can be written with respect to the horizontal and vertical response accelerations $a_H(t)$ and $a_V(t)$, acting on the centre of the mass. The accelerations can be calculated by means of various time-history calculation methods (Fajfar, 1984) for given ground accelerations (acceleration records), stiffness (vibration period) of the isolation system, mass and damping ratios. The vertical and horizontal responses each have their own maximum values that generally do not occur at the same time. In most cases, the critical combination of horizontal and vertical forces, which triggers the rocking of the object, does not occur when one of the two response accelerations achieves its maximum value. For the rocking prevention criterion, only a combination which at a certain time t causes the most unfavourable (minimum) normalized slenderness λ is relevant. Each response, acceleration depends on the stiffness and damping in a given direction (horizontal and vertical). This means that the equation of motion has to be solved for each vibration period T in a given range, for each ground acceleration record and damping in both directions.

As an example, we have determined the normalized slenderness λ for a series of five ground motion records from the 1998 Posočje earthquake (Table 1). For each ground motion record the corresponding horizontal and vertical components have been considered.

No acceleration records exist from the near-fault region of the main 1998 Posočje earthquake. The intensity of the ground accelerations near the fault was estimated to be between 0.1 g and 0.2 g (Tomaževič et al., 1999). In our analysis the peak horizontal ground components have been scaled to $a_{g,H}$ = 0.2 g. The same scale factor has been used to scale the peak vertical ground components $a_{g,V}$, so that the $a_{g,V} / a_{g,H}$ ratios remained unchanged. Figure 7 presents the normalized slenderness λ for the selected ground records, together with their mean curve and the curve obtained by the response spectrum analysis, based on Eurocode 8 (see chapter 6.1).

Table 1: Selected ground motion records for the 1998 Posočje earthquake.

Record number	Station name	ESD sequence number	Fault distance (km)	$a_{g,H}$ (g)	$a_{g,V}$ (g)	$a_{g,V}$ / $a_{g,H}$
I	Casacco – Piazza Noacco, Italy	004561	35	0.0124	0.0088	0.705
II	Gemona – Scugelars, Italy	004558	35	0.0405	0.0177	0.438
III	Gemona – Li Furmie, Italy	004559	38	0.0297	0.0129	0.436
IV	Faculty of Civil and Geodetic Engineering, Ljubljana	006235	64	0.0246	0.0078	0.320
V	Ilirska Bistrica	006236	87	0.0042	0.0022	0.537

Source: Internet 2.

We can see from Figure 7 that the mean curve gives higher slenderness as the response spectrum curve (EC8 curve) for all vibration periods *T,* and is therefore conservative. If we however consider the λ curves for each ground record separately, we can see that some ground records, especially I, IV and V give a non-conservative slenderness with respect to the one obtained by Eurocode 8. Record number V gives the most critical values for all vibration periods greater than 0.6 s. Maximum normalized slenderness is in this case approximately constant and equals $\lambda = 1.0$. This presents a notable decrease of the maximum allowable normalized slenderness. For example, if for instance $k_n = 1$ (two rows of isolators) and $k_m = 0.5$ (mass centre in the middle of the height), the allowable aspect ratio should be $H/B \leq = 2$. In this presented dynamic approach the maximum normalized slenderness depends on the actual accelerations ratio, which can be calculated only with a dynamic analysis for a given ground motion record, which should be known in advance.

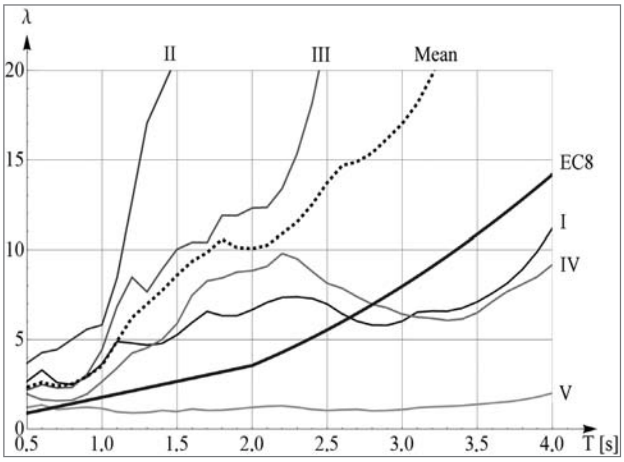

Figure 7: Maximum normalized slenderness based on the dynamic analysis for the 1998 Posočje earthquake.

7 Conclusion

As inappropriate restoration of heritage architecture can do irreversible damage to the structure, such actions should be carefully planned. It is especially desirable that the retrofit influence on the object's architecture is minimized. By following the guidelines for the protection and management of heritage architecture, held within international agreements and resolutions on conservation of monuments, we can achieve an efficient base isolation design by means of specialist research into the technological, environmental and other causes of damage, and by additional analyses which can supplement the existing renovation plans.

The design of seismic isolation system with elastomeric isolators is relatively demanding, as we are dealing with a dynamic system, in which the stiffness of the superstructure as well as the lower structure plays an important role. This article presents certain general and some special requirements for base isolation design with the use of elastomeric isolators. In slender structures with high height-to-width ratios, it is important to consider the rocking phenomenon, which is caused by earthquake forces and can lead to the liftoff of the isolators, or in the worst case scenario, the overturning of the structure itself. In such cases it is possible to determine the maximum slenderness of an object, which could still be installed on a base isolation system and would not produce any tensile forces in the isolators when subjected to an earthquake. An expression for determining the maximum normalized slenderness is given depending on the factors k_m and k_n, which represent the effect of the mass height and the effect of the number of isolators, respectively.

The maximum normalized slenderness has been determined in accordance with the Eurocode 8 response spectra, and by means of dynamic time-history analysis of the scaled records from the 1998 Posočje earthquake. We have determined that the results based on the response spectra analysis are generally conservative, although certain unfavourable combinations of vertical and horizontal response accelerations can produce also much lower maximum aspect ratios. Such situations can be predicted only by conducting dynamic time-history analyses for a given horizontal and vertical ground motion record.

We can draw towards the conclusion that the rocking prevention criterion is predominantly for the selection of bearings in cases where soil conditions are poor, the centre of gravity is high above the ground, and when the design ground acceleration in high. In other cases, the occurrence of tensile stresses in bearings is not a prerequisite condition for bearing selection. It generally holds true that isolation is not reasonable if it does not produce a significant reduction of forces compared to a non-isolated structure otherwise during an earthquake the superstructure may still be damaged. The use of bearings giving small reduction factors is of course neither reasonable nor financially justifiable from a designer's point of view.

Simon Petrovčič, Civil Engineer, Assistant
University of Ljubljana, Faculty of Architecture, Ljubljana, Slovenia
E-mail: simon.petrovcic@fa.uni-lj.si

David Koren, Civil Engineer, Assistant
University of Ljubljana, Faculty of Architecture, Ljubljana, Slovenia
E-mail: david.koren@fa.uni-lj.si

Dr. Vojko Kilar, Civil Engineer, Associate Professor
University of Ljubljana, Faculty of Architecture, Ljubljana, Slovenia
E-mail: vojko.kilar@fa.uni-lj.si

References

Amerighi, L., Gatti, V., Indirli, M., Carpani, B., Martelli, A., Spadoni, B., and Alberti, A. (2007) *The Montorio medieval tower: an architectonic study for a rehabilitation after the damage due to the 14th September 2003 earthquake*. Electronic publication. Istanbul, Anti-Seismic Systems International Society.

CEN (2004) *Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings, EN 1998-1*. Brussels, European Committee for Standardization.

Christopoulos, C., and Filiatrault, A. (2006) *Principles of passive supplemental damping and seismic isolation*. Pavia, IUSS Press.

Contento, A., and Di Egidio, A. (2008) Investigations into the benefits of base isolation for non-symmetric rigid blocks. *Earthquake Engineering and Structural Dynamics*, 38(7), pp. 849–866.

Hino, J., Yoshitomi, S., Tsuji, M., Takewaki, I. (2008) Bound of aspect ratio of base-isolated buildings considering nonlinear tensile behavior of rubber bearings. *Structural Engineering and Mechanics*, 30, pp. 351–368.

ICOMOS (1993) *Guidelines for education and training in the conservation of monuments, ensembles and sites*. Available at: http://www.icomos.org/docs/guidelines_for_education.html (Date accessed 9. 2. 2009).

ICOMOS (1999) *Burra Charter*. Available at: http://www.icomos.org/australia/burra.html (Date accessed 9. 2. 2009).

Indirli, M., Cami, R., Carpani, B., Algeri, C., Panzeri, P., Rossi, G. et al. (2006) *The antiseismic rehabilitation of Marchesale Castle at San Giuliano di Puglia*. Available at: http://www.c-spin.eu/pubs/s.giuliano.pdf (Date accessed 19. 2. 2009).

Fajfar, P. (1984) *Dinamika gradbenih konstrukcij*. Ljubljana, Univerza v Ljubljani, Fakulteta za gradbeništvo in geodezijo.

Fister, P. (1979) *Obnova in varstvo arhitekturne dediščine*. Ljubljana, Univerza v Ljubljani, Fakulteta za arhitekturo.

Internet 1: http://www.takenaka.co.jp/takenaka_e/rodin_e/index.html (Date accessed 24. 2. 2009).

Internet 2: http://www.isesd.cv.ic.ac.uk/ (Date accessed 6. 4. 2009).

Li, H., and Wu, X. (2006) Limitations of the height-to-width ratio for base-isolated buildings under earthquake. *The structural design of tall and special buildings*, 15, pp. 277–287.

Kelly, J. M. (1997) *Earthquake-resistant design with rubber*. Cambridge, Cambridge University Press.

Kilar, V., and Koren, D. (2007) Potresna izolacija stavb kot alternativa za gradnjo na potresnih območjih. *Gradbeni vestnik*, 56(12), pp. 307–318.

Komodromos, P. (2000) *Seismic isolation for earthquake resistant structures*. London, WIT Press.

Koumousis, V. (2007) *Design of the seismic isolation system for the statue of Hermes at the New museum of Olympia (paper & presentation)*. Electronic publication. Istanbul, Anti-Seismic Systems International Society.

Martelli, A., and Forni, M. (1998) Seismic isolation of civil buildings in Europe. *Progress in structural engineering and materials*, 1(3), pp. 286–294.

Martelli, A., and Forni, M. (2004) *Development and application of modern antiseismic techniques in Italy*. Available at: http://www.assisi-antiseismicsystems.org/ (Date accessed 12. 2. 2009).

Naeim, F., and Kelly, J. M. (1999) *Design of seismic isolated structures: From theory to practice*. New York, John Wiley & Sons, Inc.

Skinner, R. I., Robinson, W. H., and McVerry, G. H. (1993) *An introduction to seismic isolation*. West Sussex, John Wiley & Sons Ltd.

Tomaževič, M., Klemenc, I., and Lutman, M. (1999) Posledice potresa na kamnitih zidanih hišah: Kaj smo se naučili od potresa, *Ujma,* 13, pp. 122–128.

Zupančič, M. (2007) The Role of Structural Restoration in the Renovation of Architectural Heritage Structures. *Journal of the Protection of Monuments,* 42–43, pp. 237–245.

Zupančič, M., Kavčič, M., and Deanovič, B. (2007) *Enotna metodologija za izdelavo konservatorskega načrta*. Ljubljana, Zavod za varstvo kulturne dediščine Slovenije, Restavratorski center.