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SUSTAINABLE SEISMIC RETROFITTING OF A RC BUILDING USING PERFORMANCE BASED DESIGN APPROACH

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Abstract. In the past twenty years, sustainable development has become a challenging subject across many scientific fields. With the built environment as the major component of societies, sustainable construction has been the main player in the whole sustainability mentality. To emphasize on the importance of incorporating sustainability in to seismic retrofitting, three different retrofitting methods (base isolation, concrete jacketing, and steel jacketing) are evaluated for a typical 4-story RC school building under the 1994 Northridge earthquake's ground motion. Using Performance Based Design approach, the objective of retrofitting is to make the building perform in the Immediate Occupancy performance level according to FEMA guidelines so that it can be used as a shelter after disasters. Results show that although retrofitting by concrete or steel jacketing can control story drifts to satisfy maximum allowable values, the performance of the building and consequent damages do not meet the desired performance objective. In addition, accounting for economic and human losses, these retrofitting options will not provide a sustainable structure if a strong earthquake happens in the future. On the other hand, not only base isolation meets the desired performance objective, but also it will provide a sustainable retrofitted structure by drastically reducing economic and human losses.

Keywords: disaster risk mitigation, performance based design, seismic retrofitting, reinforced concrete, column jacketing, base isolation.

Introduction

Sustainable built environment

Sustainability is defined as "development that meets the needs of the present generations without compromising the ability of future generations to meet their own needs." (Adams 2006). Sustainable development has become an important subject in the past decades across all fields and in many different forms (Walker *et al.* 2011). As the built environment constitutes the major component of societies, sustainable construction plays a major role in the whole sustainability mentality. Aiming towards sustainable construction, sustainability should be integrated into all areas of societies and human life, and across all public and private entities, including those concerned with hazards and disaster risk management. From this perspective, hazards (natural and man-made) are regarded as threats to sustainability, and therefore, hazard and risk mitigation is in fact an important part of sustainable development. Particularly, in multi-risk regions, it is crucial to analyse potential hazards and various mitigation measures in order to assure the compatibility of measures across hazards (Walker *et al.* 2011). As an example, although elevating buildings above the ground can reduce their vulnerability against floods, this will increase vulnerability to seismic events. This is another reason why sustainability is needed to be incorporated into disaster risk mitigation.

Civil infrastructures (particularly Critical Infrastructures) have a vital role in the economy of a

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country. Structures and infrastructures are exposed to a wide range of natural and man-made disrupting events. Damage to critical infrastructure and facilities can have adverse consequences for the society and well-being of people, and is an indicator of lack of sustainability and resilience. Such negative impacts include casualties and threats to public safety, business and community functioning disruption, direct and indirect economic losses due to damage and loss of functionality, resource depletion, and so on (Padgett, Tapia 2013). Considering the diverse sources of infrastructure vulnerability and growing range of natural and technological disasters, Critical Infrastructure Protection and Resilience (CIP-R) has become an emerging topic in the recent time, focusing on vulnerability, interdependency, service continuity and recovery of Critical Infrastructure to move towards more sustainable societies (Haghpanah 2015). Mainly, these systems are designed according to specific requirements, however, it is only recently that considering future requirements and future desired performance of these critical facilities (both in design and retrofitting phases) are gaining increased attention. A wide range of performance measures is defined in this regard to properly address the sustainability and resilience of the built environment (Dong *et al.* 2013).

In the context of disaster risk mitigation, there are two main types of mitigation measures: structural measures (e.g. structural retrofitting and rehabilitation) and non-structural measures (e.g. land use planning or education). In the last decade, renovation and retrofitting of existing buildings have become one of the main activities of the construction industry. Structural retrofitting of buildings has proven to be particularly an effective measure in protecting human lives and properties (Walker *et al.* 2011). However, despite the great advances in retrofitting science, the concept of sustainability seems to be not completely incorporated. Do seismic building codes, upgrades and retrofitting projects account for future hazards and consequent requirements to meet future needs? A sustainably retrofitted building implies that the building will structurally perform well through time and through anticipated disasters, will cost less to operate, and in general, will provide a better and safer environment for people living or working in and around it.

Seismic retrofitting

Seismic retrofitting is one of the most popular and effective approaches intended to reduce damages to existing buildings. In the recent years, a significant amount of resources has been invested to support the research regarding the application of retrofitting techniques in order to improve structural performance and control seismic risks.

Among various retrofitting methods, concrete jacketing can be introduced as one of the first methods for repairing damaged concrete structures. In doing so, damaged or weak concrete columns are covered with a layer of reinforced concrete to enhance the load carrying capacity of the structure against lateral loads. In 1988, Bett *et al.* studied the effectiveness of concrete jacketing in increasing the lateral load response of damaged columns. Júlio *et al.* (2003) investigated retrofitting of columns with reinforced concrete jacketing and the results from this study lead to a uniformly distributed increase in strength and stiffness of columns. Cost benefit analysis for concrete jacketing is studied by some researches (Dadasaheb *et al.* 2013; Marques *et al.* 2017). The results show that concrete jacketing is more affordable in comparison to the other retrofitting techniques.

Steel jacketing is another retrofitting technique to improve the strength and deformation capacity of beams and columns in existing buildings using conventional and high strength steel plates, angles, and battens (Uy 2001; Foroughi, Schafer 2017; Sakino, Sun 2000). A significant number of studies have been carried out on this topic. Most of them studied the case in which angles are used in the corners and steel straps along the height of the column (Braga *et al.* 2006; Montuori, Piluso 2009; Campione *et al.* 2017).

Seismic isolation was first invented and gradually developed as an effective method for strengthening structures against seismic hazards (Islam *et al.* 2011). However, its main disadvantage is the relative complexity in design and implementation in comparison to other more conventional methods, and the fact that base isolation is not a temporary or partial solution for retrofitting. Therefore, the initial cost of base isolation is often higher than alternative retrofitting methods. That is why application of base isolation is mainly suitable for special buildings (industrial or medical buildings that contain sensitive equipment), historical buildings, and bridges (MIT LISS 2017). The core concept of base isolation is to protect the structure from damaging effects of an earthquake by improving dynamic response of the structure. This is done by installing special bearings between the bottom of the building and its foundation. Different types of base isolator devices including rubber bearing and friction pendulum and their performance against lateral loads have been studied by many researchers (Taylor *et al.* 1992; Naeim, Kelly 1999; Derham *et al.* 1985).

Performance based design

Building design to resist seismic loads has been through substantial reconsiderations in the past 40 years. Up until 1970's, design calculations were aimed to ensure that the building and its structural elements have the required strength to withstand imposed loads, specifically seismic loads, in the context of seismic design of buildings. This implies that *strength* and *performance* were considered to be the same. It was the development of capacity design principles in New Zealand (Park, Paulay 1975) that showed structural engineers were coming to understand that having a proportionate distribution of strength through a structure is more critical than just trying to reach the design base shear. Engineers came to realize that specific conditions would result buildings to perform better. For example, in a frame building, if plastic hinges occurred in beams rather than columns, the frame would perform better under seismic loads. This can be regarded as the first ideas of performance based seismic design, a different design approach in which the overall performance of the building is controlled as a function of the design process (Priestley 2000).

In conventional seismic design methods, the design criteria are defined based on limits on members' stresses and forces, and serviceability drift limits. However, there are uncertainties in code design procedures regarding seismic demand and seismic capacity of the structure (Ghobarah 2001). Recent natural disasters have proven that even when buildings are compliant with building codes, significant damages and consequent human and financial losses can occur (Arnold *et al.* 2004). Although life safety is the first priority when designing buildings, there are some specific buildings that need much better performance in earthquakes. The term "performance" refers to the condition of a building after a disaster in terms of expected level of damage (FEMA 2007). During disasters, communities rely on schools to be used as shelters, and on hospitals for treating casualties. Therefore, these buildings should be designed and constructed with different criteria so that they could continue to their function without interruptions.

Building performance is an indicator of the extent to which a structure meets the defined needs of its users. Acceptable performance indicates acceptable levels of damage that would allow uninterrupted function of the facility as was defined in the design process (Arnold *et al.* 2004). Consequently, in Performance Based Design, the design criteria are defined based on some predefined performance objectives for the structure. These performance objectives could be a maximum allowed stress, load, or displacement, a limit state, or a damage state (Ghobarah 2001). Performance-Based Design is not a substitute for design to traditional codes, but an opportunity to enhance and tailor the design to match the objectives of the users and stakeholders (Arnold *et al.* 2004).

This paper explores how different retrofitting methods will compare when taking a performance based approach. A particular building is modelled, and analysed based on a set of predefined performance objectives for a specific earthquake scenario. The structural response of the building is evaluated along with structural and non-structural damages, and economic and human losses in order to highlight long term costs and benefits for three different retrofitting methods.

1. Methodology

In this study, effectiveness of three retrofitting techniques – base isolation, concrete jacketing, and steel jacketing – is investigated for a 4-story reinforced concrete with moment resisting frame as the lateral resistant system. The building is a school located in California. The structure is 12.8 m high, 3 by 4 bays with span distance of 3.5 m; columns are 40 by 40 cm with 12 No. 6 bars (19 mm diameter) in the longitudinal direction and No. 3 bars (9.5 mm diameter) for confinement with 20 cm spacing; beams are 40 by 30 cm with 8 No. 6 bars in the longitudinal direction and similar confinement bars as for columns. The compressive strength of concrete is 21 MPa, and the bars are grade 60 steel with yield stress of 410 MPa. The column layout and elevation of the building are shown in Figure 1.

Since California is regarded as a seismic prone area, the possibility that a strong ground motion occurs is considerable. From a structural engineering perspective, this means the building should meet IBC code for strong ground motions; however, from a sustainable risk mitigation perspective, this means the building should perform better than just saving lives.

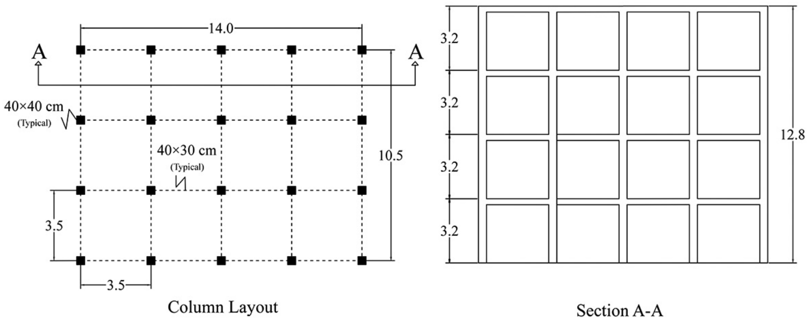

Fig. 1. Column layout and elevation (unspecified dimensions are in meters)

In emergency management, schools are often considered as the first option to be used as shelters, specifically in dense urban areas where there is not enough open space to be used as sheltering camps. Therefore, the expectation is for the school building to meet Immediate Occupancy performance level (Fig. 2) according to FEMA guidelines (Arnold *et al.* 2004; FEMA 2000) so that it could be used as a shelter with functioning utilities right after a strong ground motion (like the 1994 Northridge earthquake).

The structure is modelled and its response under the Northridge earthquake's ground motion with the considered retrofitting methods is analysed using SAP2000 software for nonlinear dynamic time history analysis. For concrete jacketing, a 5 cm layer of concrete with compressive strength of 28 MPa is added to the columns in the first story. For steel jacketing, a built-up cage is installed around the columns of the first floor consisting of four angles for the corners of the column with steel strips welded to the angles. The thickness of both angles and strips is 10 mm, and St37 steel is used. The base isolation system includes a rubber bearing isolator with 1500000 KN/m vertical linear effective stiffness, 1000 KN/m horizontal linear stiffness, and 40000 MPa yield strength.

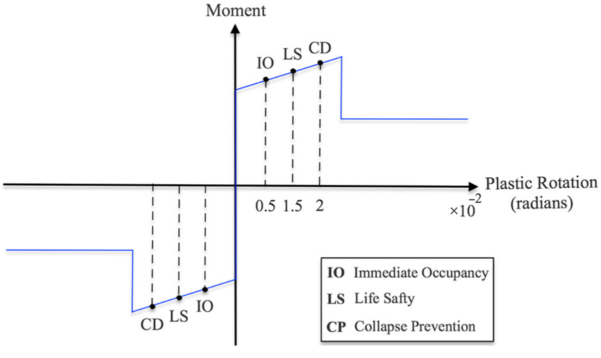

Fig. 2. Performance levels for elastoplastic behaviour of beams and columns

2. Results

Results of the analyses in terms of story drift, base shear, and status of plastic hinges developed in the structure are summarized in Table 1. As it is clear from the results, base isolation is much more effective in reducing the lateral drift and base shear in the structure than column jacketing. Base isolation reduces total drift by 65% and base shear by 70%, while these values for concrete jacketing are 17% and 6%, and 5% and 3% for steel jacketing, respectively. Moreover, in the original structure, a large number of developed plastic hinges are within the Life Safety performance level. Although this has been improved by column jacketing (concrete and steel), still the overall performance of the building is in the Life Safety level which is not satisfying the retrofitting performance objective. For case of base isolation, with no plastic hinges in the Life Safety level, the overall performance of the building is in the Immediate Occupancy level which meets our retrofitting objectives. Therefore, it is clear how base isolation can diminish the impact of earthquake on a structure by reducing deformations and consequent induced forces within the members.

Most of the hinges define on the top floor stay in the elastic domain which means no plastic rotation has been developed on the top floor columns. On the other hand, most of hinges defined on the columns of first two floors enter the plastic domain. Figure 3 illustrates the elastoplastic response of a hinge for a column on the ground floor.

Figure 4 depicts the results of the hysteresis of the nonlinear behaviour of rubber isolators. The horizontal axis shows the horizontal displacement on top of the isolators (base of the structure), and the vertical axis shows the horizontal force developed on the top of the isolators (base shear).

Table 1. Story drift, base shear, and number of plastic hinges

		Original structure	Base isolation	Concrete jacketing	Steel jacketing
4th story drift		0.009	0.003	0.008	0.008
3rd story drift		0.017	0.005	0.016	0.017
2nd story drift		0.024	0.007	0.020	0.020
1st story drift		0.019	0.008	0.010	0.011
Total drift		0.017	0.006	0.014	0.015
Base shear (KN)		8540	2490	8010	8250
# plastic hinges	IO[a]	177	100	194	200
	LS[b]	59	0	32	20

Notes: a – IO = Immediate Occupancy ($\theta_p < 0.005$); b – LS = Life Safety ($0.005 < \theta_p < 0.015$).

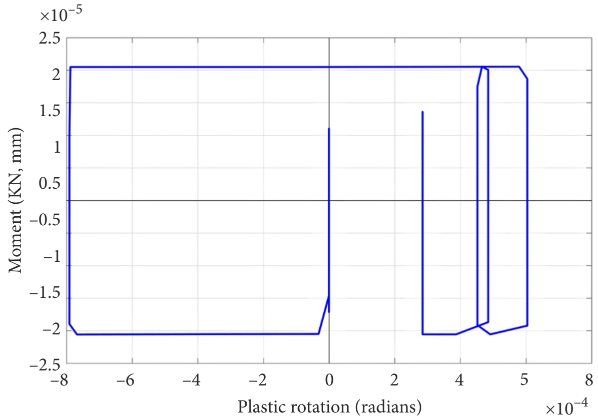

Fig. 3. Plastic hinge behaviour of a columns on the ground floor in the elastoplastic domain

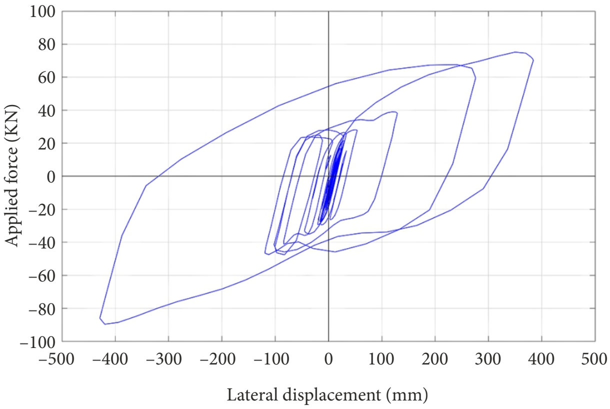

Fig. 4. Hysteresis of the nonlinear behaviour of rubber isolators

3. Damage and loss estimation

Having obtained the complete structural response, we can move forward to evaluate the damages induced on the structure due to the ground motion and consequent losses in terms of economic losses and human casualties. This is an important step in assessing the effectiveness of different retrofitting measures in seismic risk mitigation studies.

In general, four main parameters are used to evaluate the description of damage in structures: ductility, energy dissipation, relative inter-story drift, and story acceleration (Bruno, Valente 2002). In this study, relative story drift and story acceleration are used for damage and loss estimation. This is done using the HAZUS MH framework. HAZUS is the U.S. national framework for damage and loss estimation due to natural hazards developed by FEMA. It is a GIS-based software package available free to public. The technical manual of the earthquake model (HAZUS-MH 2.1. 2015) is used for evaluating damage levels and subsequent losses. The results are summarized in Tables 2 to 4. It can be seen, concrete and steel jacketing do not reduce the structural and non-structural damages whereas base isolation significantly decreases the damages to the building.

The economic losses and human injuries can be evaluated based on structural and non-structural damage levels according to the HAZUS loss estimation framework. The monetary losses due to structural and non-structural damages are evaluated based on the replacement cost of the structure which is estimated to be $2 million considering the cost of construction (reconstruction) to be $1500 to $1800 per square meter (Deierlein, Liel 2010) and cost of demolishing and cleaning-up to be $500,000 to $800,000. Cost of damage to contents is evaluated based on the contents replacement cost which is estimated to be $100,000. Cost of function disruption (repair and recovery period) is estimated to be $20,000 per day for a school building with 80 staff and students, including loss of income and wage of staff.

Table 2. Structural damage levels

Story	Original structure	Base isolation	Concrete jacketing	Steel jacketing
4	Moderate	–	Moderate	Moderate
3	Moderate	Slight	Moderate	Moderate
2	Extensive	Moderate	Extensive	Extensive
1	Moderate	Moderate	Moderate	Moderate

Table 3. Non-structural damage levels for acceleration-sensitive components

Story	Original structure	Base isolation	Concrete jacketing	Steel jacketing
4	Complete	Moderate	Complete	Complete
3	Extensive	Moderate	Extensive	Extensive
2	Extensive	Moderate	Extensive	Extensive
1	Extensive	Moderate	Extensive	Extensive

Table 4. Non-structural damage levels for drift-sensitive components

Story	Original structure	Base isolation	Concrete jacketing	Steel jacketing
4	–	–	–	–
3	Slight	–	Slight	Slight
2	Slight	–	Slight	Slight
1	Slight	–	–	–

The initial costs of installation, disruption of functionality due to installation, and annual maintenance are ignored due to the complexity of estimation. Human injuries include simple injuries to severe injuries needing multiple expensive surgeries; therefore, an average treatment cost of $100,000 per person is assumed. Cost of human fatality (or the value of life) is a controversial subject to include; however, to account human fatalities in the total economic cost, an average value of $7.9 million is considered (USEPA 2016). To account for the diversity of human injury and loss estimations, two different frameworks have been used.

It is clear from Table 5 that although base isolation is costlier than column jacketing to install, considering the consequences of an earthquake, its effectiveness in reducing the structural response is benefitting in terms of reducing the damage costs and human losses. This has been acknowledged extensively in the literature through accurate cost-benefit analyses. In a study in New Zealand (Cutfield *et al.* 2014), it is evaluated that base isolation techniques drastically reduce the annual costs of repair, and the expected benefit-cost ratio for investment in base isolation is 3.1. In another study in Peru (Bedriñana, Saito 2012), the variation of expect-

Table 5. Loss estimation for different retrofitting methods

	Original structure	Base isolation	Concrete jacketing	Steel jacketing
Structural damages	$76,000	$21,000	$76,000	$76,000
Non-structural damages	$321,000	$64,000	$316,500	$316,500
Damage to contents	$31,000	$5,000	$31,000	$31,000
Downtime costs ($20,000/days)	$2.8 million (5 months)	$650,000 (1 month)	$2.8 million (5 months)	$2.8 million (5 months)
Human injury rate (%)	0.5[a]	0.13[a]	0.5[a]	0.5[a]
	1.13[b]	0.25[b]	1.13[b]	1.13[b]
Human death rate (%)	0.00025[a]	0[a]	0.00025[a]	0.00025[a]
	0.04[b]	0.005[b]	0.04[b]	0.04[b]
Total probabilistic cost	~ $3.5 million	~ $800,000	~ $3.5 million	~ $3.5 million

Notes: a – HAZUS-MH 2.1, Earthquake Model, Technical Manual; b – Bruno and Valente, 2002 (Bruno, Valente 2002).

ed values of structural repair cost for different time windows are estimated (Fig. 5). For example, for a life time of 100 years, the total cost ratio for conventional buildings is about 4.7 times larger than that for isolated buildings.

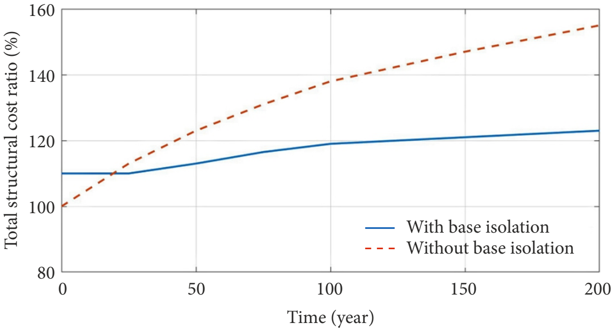

Fig. 5. Expected values of total structural cost with 10% of exceedance probability in the lifetime of the building (Luis, Satio 2012)

Moreover, it is noteworthy to highlight that since concrete and steel jacketing could not reduce damages to the building, the costs due to damages has remained quite similar in comparison with the original structure with no retrofitting.

4. Discussion

As California is a seismic prone region, the seismic retrofitting objective for this school building is set on meeting the Immediate Occupancy performance level according to FEMA guidelines. The rationale behind this objective is that schools are mainly used as shelters for victims of disasters, therefore, the shelters need to withstand the disaster such that it could continue to its function without (or just with minor) disruptions in the essential utilities. From structural response perspective, this implies that the retrofitted building should meet allowable story drift which is 0.02 according to ASCE 7 Table 9.5.2.8, and allowable plastic hinge rotation which is 0.005 radian according to FEMA guidelines for seismic rehabilitation of buildings (FEMA 2000). Moreover, from a sustainability performance, an acceptable retrofitting option should decrease economic and human losses in the long term. As results of the structural analysis show, concrete and steel jackets control the story drift to some extent, but do not meet the performance objective. When considering economic and human losses, these two methods are not able to improve the losses at all. On the other hand, not only base isolation meets the structural objectives, but also can considerably decrease the economic and human losses after a strong seismic event of the size of the 1994 Northridge earthquake.

There are uncertainties in code design procedures regarding seismic demand and seismic capacity of structures, and recent natural disasters have proven that even when buildings are compliant with building codes, significant damages and consequent human and financial losses can occur. As one can conclude, although certain retrofitting designs may be successful in controlling structural response (mainly story shear, drift, and acceleration), necessarily they are not sufficient when considering future hazards, future expectations, and future needs.

Conclusions

As sustainability has become increasingly important in building design, construction, and operation, and considering recent debates on climate change and consequent changing patterns of hazards, disaster risk mitigation has been the focus of a large body of works in sustainable built environment. The performance of critical structures and infrastructure under disruptive events can have a significant impact on the sustainability of a society. Consideration of lifetime environmental, social, and economic performance is found to be the new area of focus among researchers and practitioners (Padgett, Tapia 2013).

In this study, a 4-story educational building subjected to retrofitting is investigated, which is located in a highly seismic prone area. The possibility that a strong ground motion (similar to that of the 1994 Northridge) occurs in such seismic prone area is considerable. Although the building was designed and constructed based on standard building codes, from a sustainable risk mitigation perspective, the building should perform better than just saving lives. As schools are often considered as the first option to be used as shelters, this building should meet Immediate Occupancy performance level according to FEMA guidelines so that it could provide a shelter with functioning utilities. To this aim three different retrofitting methods are studied. Based on the results, base isolation can reduce total drift by 65% and base shear by 70%, while these values for concrete jacketing are 17% and 6%, and 5% and 3% for steel jacketing, respectively. Results of the nonlinear dynamic time history analysis show that the overall performance of the building with concrete and steel jacketing is in the Life Safety level while base isolation meets the criteria for the Immediate Occupancy level. Although instalment of base isolators costs significantly higher than column jacketing, considering the performance of the building through its life cycle and structural and non-structural damages and human casualties will give more weight to the benefits of base isolation. A cost estimation shows that the total (probabilistic) cost due to damages and human casualties would be less than a million dollars while steel and concrete column jacketing could not mitigate these costs to compare with the original, non-retrofitted building, leading to a total cost of about 3.5 million dollars.

According to results of this study and many other works on seismic retrofitting, although certain mitigation measures have relatively higher initial costs, and may require engineering expertise for design and implementation, when considering future risks, they can provide extensive benefits in terms of reduced damages and human losses. Thus, in the long term, they will yield to higher benefit-cost ratios.

Disclosure statement

The authors do not have any competing financial, professional, or personal interests from other parties.

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