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Mechanical Characteristics and Application of Fiber-reinforced Elastomeric Bearings for Seismic Isolation and Retrofitting of Bridges

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ABSTRACT

Seismic isolation is a design methodology and retrofitting philosophy that serves to decouple a structure from the strong ground motions caused by earthquakes. Seismic isolation for bridges can be achieved by placing isolators with relatively low stiffness compared to the structure itself beneath the superstructure. The low stiffness of laminated isolators increases the structural period and shift it into a range of period belongs to low seismic energy content. The objectives of this research were to investigate the effect of fiber-reinforced elastomeric bearings on the performance of an existing highway bridge in Iran. This study also made a comparison of the effect of this type of isolators with other kinds of bearings to suggest a cost-effective isolator to isolation and retrofit of bridges in developing countries which are located in seismic regions such as Iran, Turkey and so on. To this aim, a nonlinear dynamic analysis is carried out with using SAP2000 software for an existing multi-span continuous highway bridge for both non-isolated and seismically isolated with fiber-reinforced isolators. The study shows that fiber-reinforced elastomeric bearings can be replaced with other expensive type of laminated isolators. This includes more damping than steel-reinforced ones. The results of study have indicated that the seismic responses of the bridge are significantly reduced by using fiber-reinforced elastomeric bearings.

Key words: Fiber-reinforced elastomeric bearings, seismic isolation, bridge retrofitting, seismic response of bridges

INTRODUCTION

Nowadays Bridges play a crucial part during natural disasters, such as earthquakes and floods because they provide an emergency link in a surface transportation. Therefore, bridges require higher seismic performance in seismically active regions, such as Iran. The capability and benefit of isolators as effective tools of passive control for seismic forces that allows designers to decrease seismic forces transferred to the bridges is proven. Considering bridges' damages caused by earthquakes, isolators can be used effectively in bridges to improve their resistance against earthquakes. Isolators play two functions; changing natural shaking and period of bridges that leads to a descent in the level of lateral earthquake forces, also detouring and absorbing majority of earthquakes' energy which provides safety for structure against ground motions.

The effectiveness of seismic isolation and retrofitting of bridges which have more lateral stiffness like bridges with short to medium span are more sensible. This is especially considerable for bridges that are constructed on the short basis (Wang *et al.*, 1998). Although the initial stiffness of isolators on efficiency of system play crucial role, yielding force of isolators has a major impact on the efficiency and behaviour of isolated system. Yielding force controls hysteric damping of isolators, So that by using isolators with lower lateral stiffness forces and displacement of bridges' piers drop considerably. However, shaking and displacement of superstructure increases. The basic concept of seismic isolation of bridges is increasing the period of bridge, and also damping of them or both of these in a bridge (Kelly, 1997).

Base isolation and retrofitting of structures especially bridges in order to decrease the effects of strong earthquakes has become economically and technically possible and practical solution recently. It is because of developing effective laminated elastomeric bearings which are reinforced with steel layers (Naeim and Kelly, 1999). Now in many developed countries like United State, Japan, Canada base isolation is an acceptable seismic design solution in seismically active areas (Naeim and Kelly, 1999). There are many bridges that have been constructed all around the world with the concept of seismic isolation and has experienced strong earthquake that resisted safely.

Matsunohama Bridge has constructed in 1991 in Japan, which consist of four spans with a 211.5 m continuous steel deck and 22 m width. This bridge is isolated with lead-rubber bearings and reacted properly against Kobe earthquake in 1995 with PGA = 7.2 (peak ground acceleration) (Lee *et al.*, 2001).

Bolu Bridge over the Bolu pass in Turkey was isolated with hysteric steel dampers shaped C and sliding Teflon bearings. The bridge resisted an earthquake with PGA = 7.5 in 1999 and performed satisfactorily. Although this earthquake's maximum acceleration was about 1.0 g bigger than Bridge's design acceleration and it was damaged slightly, the bridge performed properly and did not collapsed.

In steel-reinforced elastomeric bearings the cost and high weight factors of isolation systems is partially related to the steel because the steel layers needs to be prepared for vulcanization bonding to the rubber basis by cutting, sandblasting and cleaning by acid (Kelly and Takhirov, 2007). The use of different fiber reinforcing materials, such as Kevlar, glass and carbon fibers has been investigated by Kelly (2002), Moon *et al.* (2002) and Mordini and Strauss (2008) instead of heavy steel layers. They found fiber materials can be a suitable replacement to steel layers to decrease the cost and weight of isolators. Kelly (1999) showed that fiber-reinforced elastomeric bearings have the same performance of steel reinforced elastomeric bearings against earthquake motions and they can be comparable. Experimental tests of fiber-reinforced bearings confirmed such theoretical works and founded that this type of isolators have the same behavior as steel-reinforced bearings and performance (Moon *et al.*, 2002; Toopchi-Nezhad *et al.*, 2008a, b).

These days the cost of retrofitting and seismic isolation are two main factors of designing structures and bearings especially in under developing countries such as Middle East countries. Therefore, the use of fiber-reinforced bearings can be suitable and cost-effective devices to the aspect of base isolation of bridges and important buildings like hospitals and fire fighting stations especially in seismically active regions (Kelly and Takhirov, 2007).

In this study, the earthquake response of three-span continuous girder bridges seismically isolated by the fiber-reinforced elastomeric bearings was investigated to find out the effectiveness of these kinds of isolators. Also results were compared to the results of other kinds of isolators to choose the cost-effective devices.

MATERIALS AND METHODS

In this study, first an existing multi-spam continues girder Highway Bridge in Iran was modeled by SAP 2000 software, then the isolated model with fiber-reinforced elastomeric isolators has been modeled. Finally, nonlinear dynamic analysis (hysteric time history analysis) was carried out to investigate the seismic response of bridge against earthquake motions.

Fiber-reinforced elastomeric bearings behavior: The main goal of constructing fiber-reinforced elastomeric bearings is providing orthotropic system with different stiffness in vertical and horizontal directions. To bear high vertical loads caused by weight of superstructures needs significant vertical stiffness while, seismic isolation needs low horizontal stiffness to allow large displacements between piers and superstructures. The response of a structure against earthquake highly depends on vertical and horizontal stiffness of bearings which are determined by designers using a static linear analysis under certain amount of load (Naeim and Kelly, 1999):

$$K_v = \frac{E_c A}{T_r},\ K_h = \frac{AG}{T_r} \tag{1}$$

where, K_v is vertical stiffness of isolator under certain amount of load, E_c is effective compression modulus, A is top surface, T_r is total thickness of isolator.

Furthermore, Shape factor of isolator is an effective factor to acquire suitable vertical stiffness. The shape factor S of a rubber confined pad is the ratio between the loaded area and the lateral surface free to bulge. For a circular elastomeric bearing, the shape factor S was calculated by the following equation (Imbimbo and De Luca, 1998):

$$S = \frac{\text{Loaded area}}{\text{Loaded area free to bulge}} = \frac{p \times D^2}{4} \times \frac{1}{pDt} = \frac{D}{4t} \tag{2}$$

where, is D is the diameter of bearing and t is the thickness of single rubber layer.

For a square shaped isolator following equation is used (Imbimbo and De Luca, 1998):

$$S = \frac{\text{Loaded area}}{\text{Loaded area free to bulge}} = \frac{a \times a}{4 \times a \times t} = \frac{a}{4t} \tag{3}$$

Shape factor is measure of slenderness in a single rubber layer of the elastomeric bearing. This parameter highly affects the general slenderness of isolator, defined by the ratio of total bearing's height to the diameter of bearing (Imbimbo and De Luca, 1998).

Reinforcing fibres produce a constraint on the free lateral expansion of the rubber. Having assumed the total incompressibility condition for a circular bearing, an equivalent compression

Table 1: Characteristics of fiber-reinforced elastomeric bearings

Isolator types	Type of rubber	Horizontal dimension	Rubber thickness	No. of rubber layer	Fiber thickness	Shape factor of isolator	K_h (kg cm^{-1})	K_v(kg cm^{-1})
A	60 Shore A	30×30	1.5	7	0.75	5	742	114780
B	50 Shore A	30×30	1.5	7	0.75	5	622	104685
C	30 Shore A	30×30	1.5	7	0.75	5	403	67535

Shure A: Standard of rubbers classified by AASHTO, K_h: Horizontal stiffness of isolator, K_v: Vertical stiffness of isolator

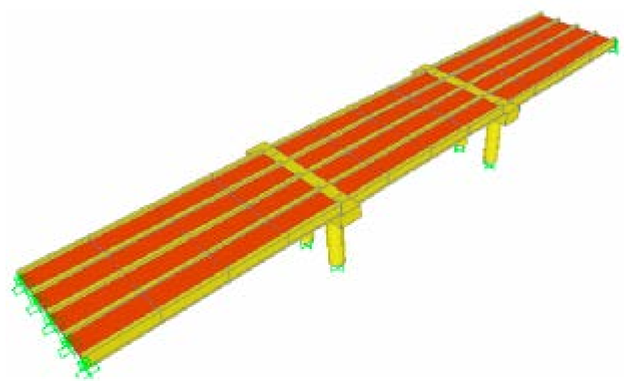

Fig. 1: Three dimensional modelling of bridge with SAP2000 software

modulus E_c was calculated for a given shape factor and rubber stiffness. The effective compressive modulus an infinitely long strip layer of elastomer bonded to the rigid reinforcement was calculated by the following equation (Kelly, 1997):

$$E_c = 4GS^2 \quad (4)$$

The effective compressive modulus for circular and square bearings was calculated by following equation (Kelly, 1997):

$$E_c = 6GS^2,\ E_c = 6.73GS^2 \quad (5)$$

Characteristics of fiber-reinforced bearings: The use of fiber-reinforced elastomeric bearings for simple and cheap earthquake isolation systems and also retrofitting of structures has been discussed a lot. The advantages of the use of fiber reinforcement for these isolators (e.g., high damping, large range of horizontal deflection) are known and have often been described. However, the current design codes give no appropriate formulas to calculate the behaviour of fiber-reinforced elastomeric isolators.

In this study three types of fiber-reinforced elastomeric bearing which each of them comprises different stiffness of rubber were modelled using SAP2000 software between piers and deck of an existing highway bridge in Iran. To show the effectiveness of retrofitting of bridges by these isolators, nonlinear time history analysis of bridge has been carried out. The characteristics of isolators are given in the Table 1.

Bridge characteristics: A typical under operation three-span Highway Bridge located in Iran with 20 m span is used in this study as shown in Fig. 1.

The superstructure consists of 200 mm continuous composite slab with 5 girder beam supported on two continuous concrete girders. The depth of the continuous concrete girder is 1000 mm. The substructure of bridge consists of rigid abutments at the two ends and two intermediate reinforced concrete piers. The footings are supported on pile foundation. Three types of fiber-reinforced elastomeric bearing with different rubber stiffness are considered under girders to decouple superstructure from earthquake motions.

Modelling of non-isolated and isolated bridge with fiber-reinforced elastomeric bearings: In the past decades it is assumed that rubbers lose their resistance completely in seismic loading. This leads to a common design attitude against seismic loads in Iran in which positive or negative effects of elastomers are ignored (i.e., modelled as simple fixed or sliding hinges). Therefore, connection between substructure and superstructure assumed to be free to move at abutments and joint at pier top and only pier inertia resists longitudinal movement. In this method of modelling, abutments carry only vertical loads and they are designed under soil pressures acting on abutment wall.

In case of retrofitting the bridge, superstructure is supported by elastomeric bearings, so that stiffness's of the elastomeric bearings contribute to the overall bridge stiffness. Elastomeric pads are considered in computer analysis (with link elements connections between substructure (abutments, piers) and superstructure in which their characteristics are definable in different directions. With this method of modelling changing in stiffness of isolators could affect the fundamental period of the bridge and earthquake load and consequently the design of the bridge.

The constraint conditions of the model without the elastomeric bearings are restrained in three directions, so the longitudinal and transverse movement of the stiffening girder can be partly restrained by isolator. It helps to avoid the large displacement of deck.

Earthquake ground motions: Three historical earthquake records are used in the subsequent analysis. These three ground motions refer the earthquakes occurred in Iran, with different PGA (peak ground acceleration). The first one occurred in 1978 in the city of Tabas in Iran with PGA of 0.933 g value and duration of 25 sec. The second one occurred in 1977 in Naghan with PGA of 0.723 g value and duration of 5 sec. The third one occurred in 1990 in Manjil with PGA of 0.514 g value and duration of 53.5 sec. In order to consider the variation of the amplitude, phase characteristics of different ground motion histories are applied into the modelled bridge to evaluate the seismic responses. Figure 2 shows typical ground acceleration time histories of three earthquakes.

A non-linear time-history analysis was carried out in this study on a non-isolated existing highway bridge in Iran and isolated model of that bridge which isolated with three different isolators that differ in rubber stiffness. The aim of this research was investigating the effectiveness of fiber-reinforced elastomeric bearings and find out the effect of rubber stiffness on the bridge response under earthquake excitation. The analytical non-isolated and isolated models were prepared with CSI SAP2000 software and time-history analysis were carried out for both models. The time histories (acceleration, displacement, piers shear forces, maximum displacements and maximum load in isolators) of the considered ground motions are derived to assess the effectiveness of retrofitting method.

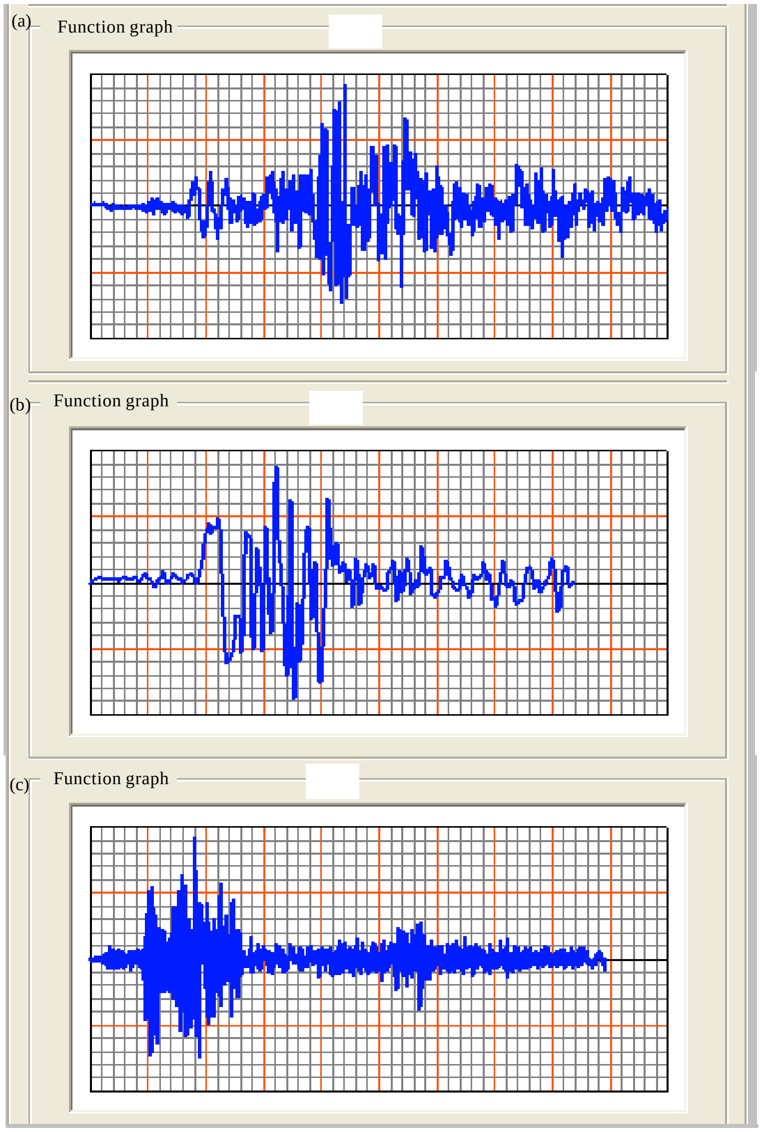

Fig. 2(a-c): Acceleration time histories of three earthquake records in Iran, (a) Tabas, (b) Naghan and (c) Manjil

RESULTS

This study presents the response of non-isolated three-span continuous Girder Bridge and its seismically isolated models by laminated fiber-reinforced rubber bearings which acted upon by earthquake ground motions. Three different types of fiber-reinforced elastomeric bearings are used to investigate the effect of isolation over bridge system. These bearings are modelled using the design equation specified by Kelly (1997) and Naeim and Kelly (1999) for highway bridges. It should be noted that a set of parameters corresponding to design models are estimated using the design equations as specified in that references. In this study, the bridge responses are discussed in terms of the base shear force of bridge, deck acceleration, displacement of deck, isolators and pier's force, since these responses are predominant for seismic design of bridge systems or retrofit

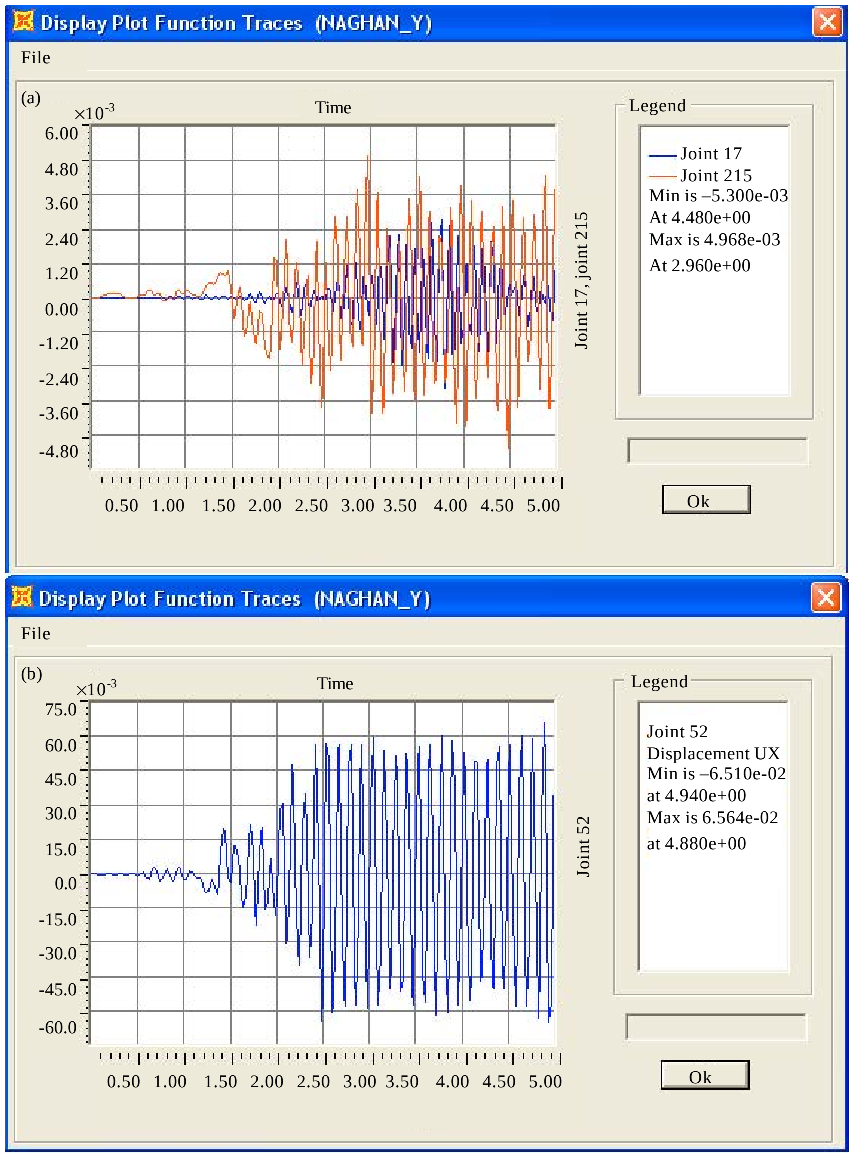

Fig. 3(a-b): Time history-displacement graph of external girder at mid pier for Tabas earthquake in Y direction, (a) Time history-displacement of top of the isolator (red) and bottom of the isolator (blue) and (b) Time history-displacement of non-isolated

old bridges. The effect of fiber-reinforced elastomeric bearings on the responses indicates that retrofitting reduces the response of stiff bridge system significantly like steel-reinforced elastomeric bearings and can be used effectively to design a safe bridge system. As these types are lightweight and the cost of produce are lower than steel-reinforced type, they could be suitable choose to retrofit and seismically isolation of bridges.

Figure 3a and b illustrate time histories of relative displacement on top of fiber-reinforced bearings (between fiber-reinforced bearing and girder) and bottom of fiber-reinforced elastomeric bearings during grand motions of Tabas and Naghan. It can be found that with installation of fiber-reinforced elastomeric bearings, relative displacement can be reduced to some extent.

Table 2: Base shear forces of isolated and non-isolated bridges

		Isolated bridges (Ton)		
Ground motion	Non-isolated bridge (Ton)	A	B	C
Longitudinal Tabas E.Q	491	430.5	401.1	360.5
Longitudinal Naghan E.Q	482	358.0	341.7	336.5
Longitudinal Manjil E.Q	515	372.8	360.5	332.9
Transverse Tabas E.Q	840	530.0	416.0	335.0
Transverse Naghan E.Q	812	348.0	336.0	302.0
Transverse Manjil E.Q	807	341.0	348.0	337.0

Table 3: Maximum shear force of isolators and displacement of isolators due to three ground motion

	Maximum shear forces of isolators			Maximum displacement of isolators		
Ground motion	A	B	C	A	B	C
Longitudinal Tabas E.Q	12800	9250	5900	18.20	14.80	15.22
Longitudinal Naghan E.Q	4800	4603	2945	7.12	7.19	7.48
Longitudinal Manjil E.Q	5765	5255	2984	8.28	7.98	7.14
Transverse Tabas E.Q	12300	9842	5800	17.40	14.90	15.80
Longitudinal Naghan E.Q	4750	4600	2850	7.42	7.18	7.40
Longitudinal Manjil E.Q	5551	5112	2913	7.99	7.78	7.43

The results of time history analysis based on base shear forces of isolated bridge with fiber-reinforced elastomeric bearings at the bottom of the piers and non-isolated bridge are shown in Table 2. Compared to the time histories of base shear forces of model without fiber-reinforced elastomeric bearings, shear forces of isolated bridges are considerably reduced. It can be seen that longitudinal base shear force for non-isolated bridge is 491 Ton in Tabas earthquake and 430.5 for isolated bridge modelled with bearing type A. This amount for isolated bridge with isolator type B is 401.1 Ton and for bridge with isolators type C is obtained 360.5 Ton. The results for Naghan earthquake are derived about 482 Ton for non-isolated bridge, 358, 341.7 and 336.5 Ton for isolated bridges, respectively with isolators type A, B and C. While, for Manjil earthquake, longitudinal base shear is around 515 Ton for non-isolated bridge and 372.8, 360.5 and 332.9 Ton for isolated bridges with isolators type A, B and C. Results show about 12.5 percent decrease in base shear force for retrofitted bridge with isolator type A during Tabas earthquake. This decrease for isolated bridges with lower vertical stiffness isolators are slightly higher, 18.5% retrofitted bridge with isolator type B and 26.5% with isolator type C. The reduction for longitudinal earthquake ground motions during Manjil earthquake are around 27.5, 30 and 35.5%. This pattern can be seen during the transverse motions, while the amount of decrease is higher than longitudinal ground motions.

Taking financial concerns into consideration, it should be mentioned that the reduction amount in the shear forces are substantial that leads a cost-effective design of structures. In addition, seismic resistance design aspect of structure is also provided.

As it can be seen from the Table 2 there is a considerable decrease in the amount of the base shear forces of the bridge with fiber-reinforced elastomeric bearings. It is obvious that the majority of loads are because of the deck and girders of a bridge since installation of isolators cause magnificent fall in the motion of deck. Such that for transverse ground motions it is around 40-70%. Therefore, the amount of base shear forces decrease highly during earthquakes.

Table 3 indicates maximum shear forces and displacements of installed isolators in the bridges. It can be seen that increasing the stiffness of isolators leads to resist higher shear forces. As

Table 4: Maximum shear forces of mid pier and moment at the bottom of mid pier of isolated and non-isolated bridges

		Mid pier of isolated bridges (Ton)		
Ground motion	Mid pier of non-isolated bridge (Ton)	A	B	C
Tabas E.Q	106.4	67.8	66.3	62.0
Naghan E.Q	108.0	65.2	62.8	58.5
Manjil E.Q	110.0	64.1	62.2	57.3
		Mid pier of isolated bridges (Ton-m)		
	Mid pier of non-isolated bridge (Ton-m)	A	B	C
Tabas E.Q	390.60	211.3	207.1	199.8
Naghan E.Q	382.50	261.2	248.1	228.8
Manjil E.Q	3471.7	242.4	236.2	220.7

Table 3 shows isolator type A resist approximately twice shear force more than isolator type C. It should be considered that the stiffness of isolator type A is around twice more than the stiffness of isolator type C, 114780 and 67535 kg cm^{-1}, respectively. Table 3 also indicates that isolators' displacements are closed to each other. This means that to respond higher earthquakes that cause higher shear forces, using isolators with higher stiffness are suitable than isolators with low stiffness. Therefore, these kinds of isolators are eminently suitable for retrofitting purpose because manufacturing of isolators with higher stiffness are possible just with increasing fiber layers without increasing the dimension.

Period of structure is obtained 0.21 second for non-isolated bridge and for isolated bridges with isolator type A, B and C are 1.33, 1.39 and 1.72, respectively. It is clear that the periods of isolated bridges are considerably more than the non-isolated one. The reason is increasing flexibility of deck by installing fiber-reinforced elastomeric bearings that cause structure not stand in predominant period of earthquakes. So that, the effects of ground motion into the structure decrease such that they can be very beneficial devices to retrofit the bridges.

Time histories of shear forces for mid-piers and their moments at the bottom are given in Table 4. Compared to the non-isolated one there is a considerable decrease in the amount of shear forces of piers. It originates from decreasing of deck displacement that results to low effects on the piers.

The largest shear force of piers for non-isolated bridge is 106.4 Ton, while during Tabas earthquake maximum shear force for bridges with fiber-reinforced elastomeric bearings type A, B and C are 67.8, 66.3 and 62 Ton (approximately 40% decrease). Table 4 dedicates that with decreasing the stiffness of isolators, base shear forces and moments at the bottom of piers decrease significantly. However, that causes large amount of displacement. Therefore, it needs an optimal range of stiffness and displacement of isolators to meet design standard. This is also theoretically describable such that decreasing stiffness causes a growth in period of structure. Consequently, natural frequency of structures decreases and causes an increase in the amount of ω/ω_n and a decrease in the TR (transfer coefficient). On the other hand, to bear higher vertical loads isolators with higher stiffness are needed.

Time histories of moment at the bottom of the mid pier also are shown in Table 4. Compared to time histories of the moment of models without fiber-reinforced elastomeric bearings, moments of retrofitted bridges are considerably reduced. The largest moment for non-isolated model of bridges is 390.6 Ton m, and during Tabas earthquake it reduces to 211.3, 207.1 and 199.8 Ton m, respectively for isolated bridges with isolator type A, B and C. The results show around 46% decrease. As it can be seen from the Table 4, with decreasing stiffness of isolators the amount of decreasing in forces increase significantly. These reductions are considerable in designing of structures and also retrofitting of existing structures which moves the structure into earthquake resistant domain.

DISCUSSION

In this study, multilayer elastomeric seismic isolators, reinforced by layers of carbon fibers, were installed in an analytical model of existing Highway Bridge by using SAP2000 software to retrofit the bridge. Consequently, the effects of fiber-reinforced elastomeric bearings on the performance of bridge were examined by performing nonlinear time-history analysis.

Investigation of the effect of rubbers stiffness and shape factor of isolators indicates that raising the stiffness of rubbers increases the value of vertical stiffness for fiber reinforced isolators. By increasing the stiffness of rubbers from 35 to 75 shure A, the value of vertical stiffness has increased about 96%. Moreover, for models with 35 shure A, by increasing the shape factor from 6.25 to 30, the effective compression modulus increases by about 515%. These findings are hardly comparable to other studies due to lack of sufficient information. However, the relations found and proposed by both Kelly (1999) and Tsai (2004) confirm these trends.

Numerical investigations reveal that fiber-reinforced elastomeric bearings may positively affect the seismic response of such bridges; this effects highly depends on geometry of bridge, especially the rigidity of piers. For the selected bridge example, the fundamental period is elongated by 85% and therefore, internal forces such as shear forces and moments are reduced approximately 40-60%. The same results were found by Akoglu and Celik (2008). They showed that for the selected bridge example in Turkey, the fundamental period is elongated by 80% and thus internal forces are reduced by 60%. They also showed that in bridges with tall and flexible piers elastomeric bearings may increase stiffness of isolated system by adding extra stiffness to them. In theses cases, because lateral loads are distributed appropriately between the piers, shear forces at the base of piers decline significantly (around 50%). So that elastomeric bearings are suitable and effective devices to decouple bridges with short and rigid columns from earthquake motions.

In this study bridge responses are discussed in terms of the base shear of the pier, deck acceleration, displacement of deck and pier top force, since these responses are predominant for seismic design of bridge systems. The effect of fiber-reinforced elastomeric bearings is significantly observed in the responses indicating that isolation reduces the response of stiff bridge system significantly and can be used effectively to design a safe bridge system. Haque *et al.* (2010) provided similar bilinear models of laminated elastomeric bearings such as LRBs (lead rubber bearings) and HDRBs (high damping rubber bearings). Their results confirm the effectiveness of laminated elastomeric bearings for improving the response of bridges.

Results of the retrofitted with comparison to non-isolated bridge showed that the bearings were highly effective at reducing the response of the structure. The lowest level of efficiency obtained from the results of the data was a 20% reduction for base shear during the longitudinal selected ground motions and around 60% for transverse ground motions. Also installing the fiber-reinforced elastomeric bearing elongated the fundamental period of structure about 85%. Similarly Foster (2012) conducted a M.S thesis to identify the effect of steel-reinforced rubber bearings on the performance of bridges. They showed that the lowest level of efficiency obtained from the results of the data was a 66% reduction for base shear. The highest level of efficiency was in Montreal, where an 86% reduction for spectral acceleration was achieved.

In this study damage conditions of piers and formatting of plastic hinges in piers were not studied. As piers are one of the most critical parts of bridges investigating of plastic hinges in piers are quite important. Also, supporting of decks against large displacements that occurs in some earthquake accelerations should be probed precisely. Therefore, these conditions need to be investigated in upcoming studies.

CONCLUSION

Bearings composed of several elastomeric layers bonded to reinforcing sheets are widely used in many engineering applications. While, in most of the earlier applications, steel shim plates have been used as reinforcing layers in laminated bearings, recent studies propose the use of flexible fiber reinforcement. In this way, it is believed to be possible to produce both light-weight and cost-effective isolators to be used in low-cost housing and bridges.

Although, the flexible reinforcement assumption is a fairly reasonable assumption in the analysis of a fiber-reinforced elastomeric bearing, it is necessary to indicate the effect of behavior of isolators on the performance of structures. This study investigates the effect of fiber-reinforced elastomeric bearings on the performance of an existing highway bridge in Iran.

Nonlinear time-history analysis conducted on isolated and non-isolated bridge shows that these kinds of elastomeric bearing are capable to reduce the effect of earthquake on the bridges. Such that, they decrease the effected ground motions considerably to the isolated bridge. The fiber-reinforced bearings satisfactorily restrained the deck displacement and the relative displacement between the deck and the pier for strong ground motion. Also the shear demand on the pier decreased significantly by using the bearing, they can safely restrain the deck from falling off the piers during strong earthquakes. Therefore, they are suitable devices in order to isolate bridges and retrofit existing bridges.

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