

Investigation of Seismic Behavior of V-Shaped Bridge with Memory Alloy Separator in Earthquake Orientation -Affected Joints

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Abstract:

In recent decades, widespread damage to structures due to destructive earthquakes has encouraged researchers to use seismic control systems. One of the most important structures is bridges, which should maintain their service after severe earthquakes. One of the ways to control the bridge is to isolate the deck from the substructure, which results in high displacements at different points in the bridge and the residual displacements within the separator itself, thus requiring repair and replacement of these systems after severe earthquakes. Therefore, the use of new seismic separation systems on bridges has always been important. The purpose of this project is to utilize a new memory-shaped seismic separator system to investigate the seismic performance of v-shaped column bridges, in which case the effect of earthquake orientation and its effects on responses the earthquake will also be assessed. Due to the ever-increasing advances in various intelligent materials, such as shape memory alloys, and their unique capacities, such as back-centering, and high fatigue and corrosion resistance, in this study, these materials have been used as a complementary component along with lead core separators. The shape memory alloy has been used as 4 vertical rods that connect two separating parts to each other and in this research the diameter and location of these rods will be calculated using optimization algorithm in Matlab software.

Keywords: V-shaped bridge columns, bridge junctions, shape memory alloy, seismic separator, seismic performance.

1. Introduction

Bridges are vital arteries of any nation's transportation network whose destruction is caused by a strong earthquake when they are most needed to provide emergency services or assist in evacuating a damaged area, are leading to the disconnection of these vital arteries. Hence, a new technology called seismic separation was invented as a scientific and cost-effective alternative to the seismic design and optimization of highway bridges. With the use of seismic separator supports on the bridges, the ductility increases and the earthquake forces applied to the bridge structure are reduced. This will improve the seismic performance of bridges under strong earthquakes to provide emergency relief after an earthquake. The separator supports on the bridge are a mechanical device whose task is to transfer the support reaction and lateral forces to the bridge deck. The provision of separators can increase its seismic efficiency. Regarding the characteristics of the separators, the ability and

advantages of the separator support as a lateral forces control tool allow designers to reduce or deflect earthquake forces into the piers and abutments bridge, well proven.

These supports can be effectively used to reinforce existing bridges or design of new bridges structure in seismic areas. Separator supports used for seismic bridge separation are usually located beneath the bridge deck and on piers and abutments. Due to the nonlinear behavior of these separators, the reduction of the displacement effect and the existing residual forces due to the plastic strains will decrease the separator replacement costs, thus the ability of the shape memory alloys in their self-recursive behavior. To reduce these effects. Thus, the ability of the shape memory alloys to utilize in their recursive behavior can be used to reduce these effects.

3 – Literature

Various researchers have evaluated the types of connections in bridges and their impact on the seismic behavior of bridge. Zahraie and Sami in 2008 in a study entitled (Evaluation of seismic performance of bridges with available thermal expansion supports) examined the seismic behavior of bridges separated by thermal expansion bearing (Neoprene) and Partial and limited usability. The results of the analysis showed that the efficiency of existing thermal expansion bearings was not efficient in reducing the seismic response and even if it was possible to necessary slip and tolerate large shear strains in their during the earthquake due to the linear elasticity of the force-displacement behavior, damping and depreciation did not have much energy and cannot significantly reduce the earthquake energy level and the shear force applied to the bridges infrastructure, while the separators' contribution to the earthquake input energy absorption and dissipation is greater than 50% [1].

In 2012, Sazarrin et al. Conducted the research (Performance of Bridges with Seismic Isolation Supports under the Chilean Maulé Earthquake) [2]. The results showed that the acceleration recorded at the top of the deck was about twice the acceleration recorded at the bottom of the pier bridges, indicating a favorable seatings performance. Although the extracted design spectrum had larger values than the design spectrum, the bridges did not suffer any damage due to the optimum performance of the separators. Most of the damage to the bridges in the area was due to insufficient seating in the piers and abutments leading to a revision of the design regulations, adapted from the Japanese regulations [3].

In 2012, Wei and Buckle conducted the research (a simplified method for analyzing bridges with elastic infrastructure). The research indicates that seismic separators

are a new design approach to reduce the impact of earthquakes on structures. This means that to reduce the seismic demand on the structure, its capacity will be increased, thereby preventing the collapse of the structure and reducing human damages. In this research, a method has been developed that incorporates all the important features of the general design method presented in the Ashto regulations . Numerical investigation of this method demonstrates the considerable satisfaction of the assumptions used in it and confirms the initial design approach of the separated bridges when the elastic column performance is expected [4]. It can also be said for elastomeric separators, the flexibility of elastomeric seismic separator bearings, the main period lengthens the seismically separated buildings and bridges and reduces earthquake forces at the superstructure. Although, this decrease may be associated with large horizontal displacements of the separators, but lateral flexibility plus horizontal displacements results in a significant reduction of the critical buckling load capacity of the elastomeric separators [5 - 9]. Eröz and Disruchiz in 2013 [10] investigated the seismic performance of friction pendulum support (FPS) as representative of sliding separator supports and Lead Rubber Bearing (LRB) as representative of elastomeric supports.

They found from their study results that the frictional pendulum separator (FPS) is able to adapt to the vertical components of strong ground motion, which may result in a buckling failure in the (LRB). Therefore, the omission of the vertical component of ground motion in modeling and behavioral analysis (LRB) may lead to the neglect of a buckling failure mode. Shiravand and Rasouli in 2019 (Influence of Infrastructure Mass Involvement on the Natural Period of Multi-Column Separator Bridge with Base Separator) to investigation of the Mass Participation Effect of Bridges Structural Components that includes four elements of bridge column mass, The mass of the cap beam, rotational moment of inertia of the bridge and the rotational moment of inertia of the cap beam.

In this case, by providing a hybrid separator system, they reduce the impact of these structural components on the main period of the structure which may increase the damage to the bridge structure [11]. Impact of these structural components Choi proposed a new concept of separator in 2006, in which wires are used in combination with elastomeric support to control instability and irreversible deformation [12]. They stated that they inhibited rubber SMA supports, deck displacement, and relative displacement between deck and pier. Also the leave no residual deformation

even after intense ground movements, lead core supports, however, usually show great permanent deformation after large earthquakes and need to be replaced. In 2011, Hurlbaeus and Herlabas declared the SMA Rubber Restraint System (SRB) to be effective in protecting bridges shakes in near-earthquakes. They investigated the sensitivity of bridge shake response with parameters such as conversion power, conversion displacement, SMA device pre-strain level, ambient temperature and lateral hardness of the rubber support [13].

Mishra Shinozuka in 2014 calculated the stochastic response of an isolated shear building frame with SMA- Lead core support (SMA-LRB) under random earthquakes. For this purpose, the stochastic response of a building model separated by the SMA-LRB system, with nonlinear stochastic linearization of the SMA nonlinear force-displacement curve, determined under nonlinear stochastic vibration, and the effectiveness of SMA have been demonstrated by investigating the improvement in separator performance. It has been found that SMA-LRB greatly reduces the displacement of the separator against a slight decrease in efficiency compared to the conventional LRB [13].

4 - Characteristics of the investigated system

4.4- Bridge Specifications

In this study, a bridge with one path and a completely symmetrical and similar return path with no connection or constraint between the two paths is used. The modeled part of the bridge is 30 meters is considered, because the main bridge from which the which the section under investigation is separated has 5 spans, with 24.5 meters at the beginning and end spans and 30.0 meters at the middle of the spans. with 24.5 meter, first and last openings and 30.0 m wide middle openings. And middle three spans with a length of 30.0 m. This overpass bridge has 7 reinforced concrete support piers for the deck shown in Fig. (1) with its dimensions.

According to Fig. (1) the columns used in the piers are V-shaped that their dimensions are 0.68 meters by 0.68 meters and the thickness of the reinforcement cover is 7.5 cm. The bridge superstructure for a route, consist of 5 original concrete beam across the center to the center of 2.5 meters apart and a 20 cm concrete beam. The total weight of the superstructure was calculated for two routes equal to 51,000 (kn) (5100 tons) and for one route equal to 25500 (kn) (2550 tons). Also, the live load of the bridge was calculated in accordance with the Rules of the Ashto

regulations and was calculated to be 12000 (kn) (1200 tons) for one route. In this case, to investigate the results connections of the part substructure part with part superstructure, two rigid and semi-rigid joint modes have been used. In semi-rigid joints, two Lead-rubber separator (LRB) and Shape-memory alloy-LRB separators are used that the schematic of their positioning can be seen in Figure (2).

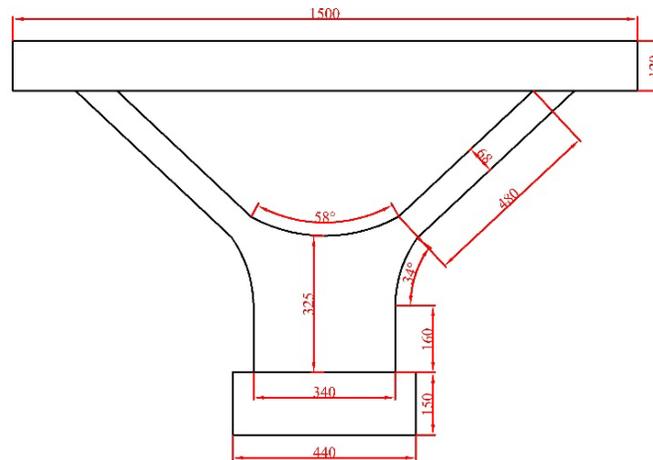


Figure 1: Overview of the investigated bridge.

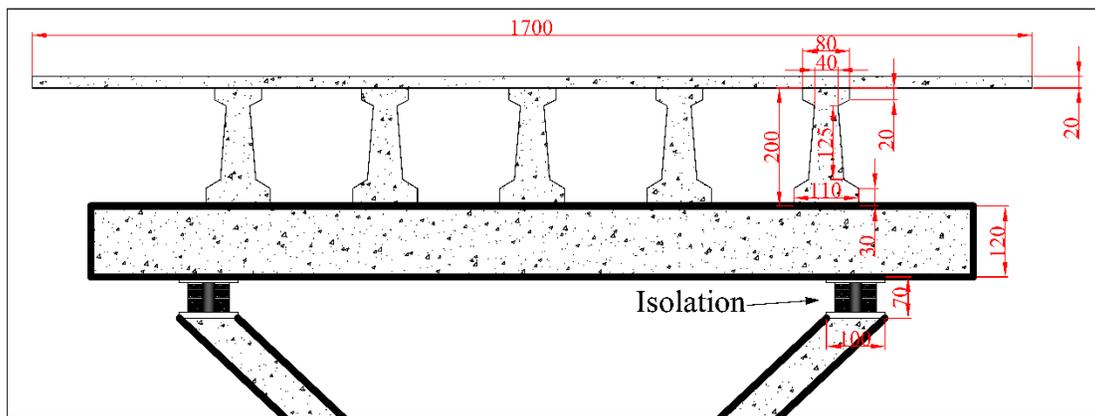


Figure 2: How to connect the substructure with the superstructure.

4-2- Semi-rigid connections

Rubber-lead separator is the most common seismic separator in the world. The product was invented in the 1970s by Dr. Bill Robinson and was known worldwide as the "lead core". Today, one of the most reliable and efficient seismic protection

equipment is a variety of structures. The rubber-lead separator consists of a lead core located in the elastomeric layers. The lead core performs the task of damping energy under rigid operating loads and under severe lateral loads. The upper and lower steel sheets, which are thicker than the inner layers, are used for connecting parts for separator installation and operation. The most important limitation of elastomeric supports and elastomeric supports armed with steel plates is their damping value. This type of support with a damping of about 5% cannot absorb much energy, with the use of lead core elastomer it increases the damping value by 21 to 25% and as a result absorbs and depreciates a portion of earthquake energy. The following equations will be used to calculate the design values of the LRB separator.

$$D_D = \frac{g}{4\pi^2} \times \frac{S_{ID} * T_D}{B_I} \quad (1)$$

Relation (1) is to calculate the displacement plot of the LRB separator in which g is the acceleration of the earth, the zone risk parameter, the period of the bridge structure, and is equivalent to the percentage of damping that is obtained from the research presented by () for the percentage of different dampers is extracted. The (2) to (6) relation will be used to calculate the area of lead core.

$$W_D = 2\pi D_D^2 * B_{eff} \quad (2)$$

$$Q_d \cong \frac{W_D}{4D_D} \quad (3)$$

$$K_d = K_{eff} - \frac{Q_d}{D_d} \quad (4)$$

In the above equations, the W_D values indicate the amount of energy dissipation in each separator response cycle, equal to the lead yield strength and the secondary hardness of the separator, which K_{eff} equal to the effective hardness of each separator. In this case the core diameter value will be calculated from (5).

$$D_y = \frac{Q_d}{K_v - K_d} \quad (5)$$

After introducing the parameters needed to calculate the core level values of the LRB separators, we will continue to examine the properties of the SMA materials. more

than ten different types of shape memory alloys have been identified at present, but only a few have been of interest to civil engineering, of which Nickel-Titanium, Fe-Mn-Si and Cu-based alloys noted. The Ni-Ti is often preferred for seismic applications due to its extremely elastic properties and excellent resistance to fatigue in high pressure cycles [14-16]. These alloys have a certain behavior under the applied forces, which can be seen in their stress-strain curve in Figure (3).

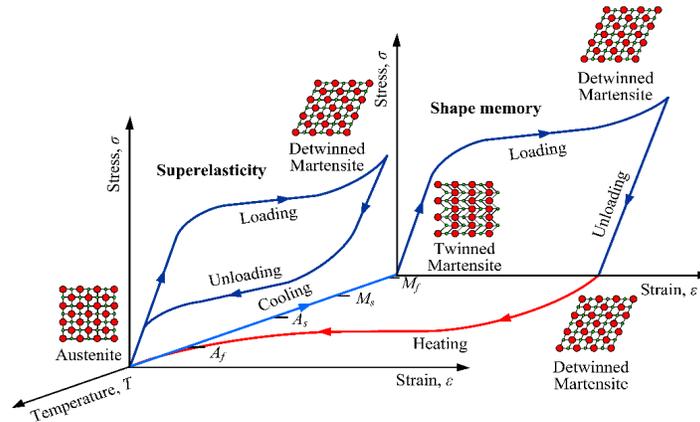


Figure 3: Examination of the stress-strain diagram of super-elastic aggregates and shape-memory alloys.

In this study, the experimental results presented by () will be used to model the Ni-Ti-SMA behavior, which in the table (1) shows the parameters for Ni-Ti behavior.

Table 1: Characteristics of the memory alloy aggregates behavior presented in the research [17].

value	unit	parameter
60000	MPa	E
520	MPa	σ_S^{AS}
600	MPa	σ_f^{AS}
240	MPa	σ_S^{SA}
200	MPa	σ_f^{SA}
8	%	ε_L

The use of memory alloys to aid the behavior of separators has been investigated in several studies. In the first step, how the memory alloys are placed in the separators is of particular importance. In this study, rods were used to add the super elastic behavior of these alloys, the number and diameter of these rods using Matlab software will be optimized.

5- Behavior of separators

The mechanical behavior of the SMA-LRB largely depends on the mechanical behaviors of the LRBs and SMA elements, which are combined in accordance with the design strategy chosen. Here, the mechanical behavior of SMA-LRB is evaluated numerically for a range of parameters used in practice. The maximum displacement created in the separators (Δ) is determined as the main parameter for optimization, which varies between 0.1 and 0.5 m. The amount of stress created in SMA bars in each placement strategy is taken as another objective function in optimization. Design relationships of LRB separators and modeling parameters of memory alloys are provided.

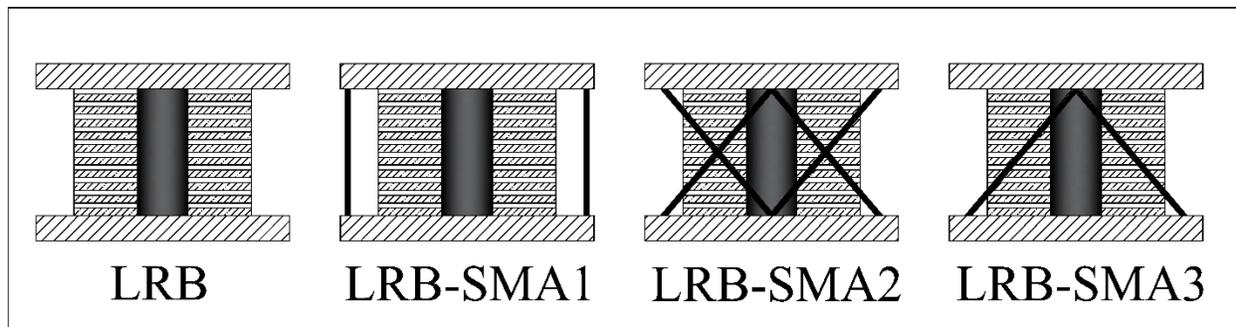


Figure 4: Different configurations examined for SMA-LRB.

Based on the above, the objective is to optimize the reduction and select the best shape of SMA bars within the SMA-LRB configuration, which can then be seen in how SMA is positioned and volume applied. Based on the results presented at different displacement values and stresses in the studied separators and computing their results as in Fig. 4 of this set of results and genetic optimization algorithm in Matlab software ,configuration (3) and bars with the diameter (15 mm) has the most optimum stress and displacement values created in the SMA-LRB and therefore this strategy will be used in V-shaped bridges.

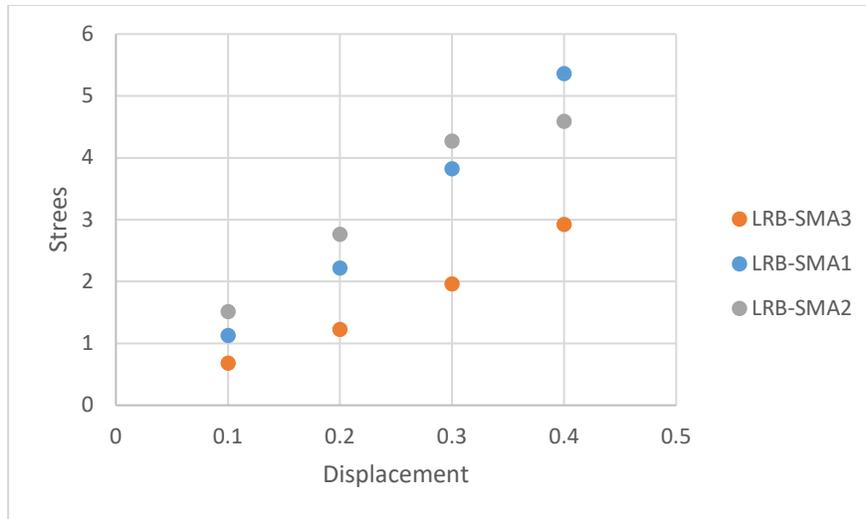


Figure 4: Changes of stress to displacement at a fixed diameter for SMA rods in different LRB-SMA configuration.

In Fig. 5, the results of the proposed LRB and SMA-LRB separator hysteresis responses with Optimal design parameters are presented, in which case the desired configuration is based on the results obtained from optimization of type (3).

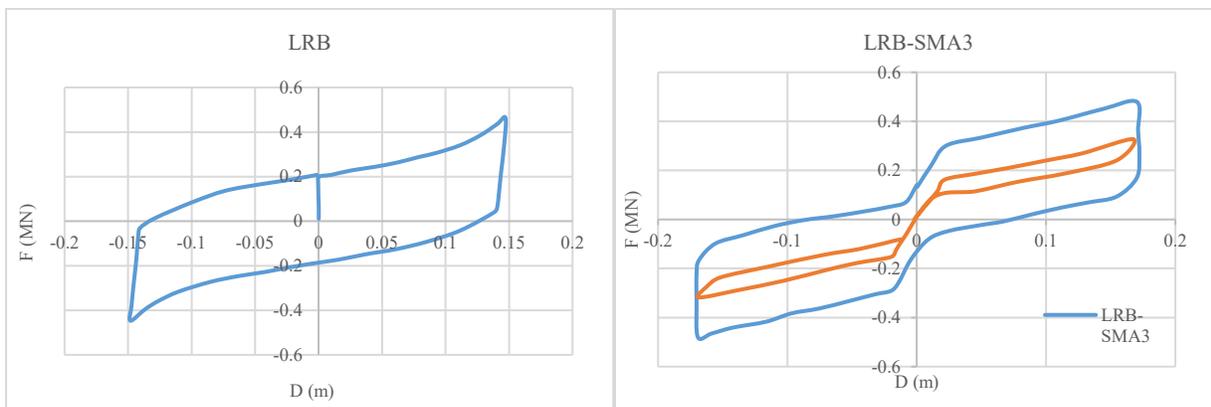


Figure 5: Hysteresis responses of the investigated isolates.

6. Seismic response evaluation

In order to evaluate the efficiency of the proposed bridge response systems under different earthquake records, the response of different bridge systems is compared. In order to evaluate the efficiency of the proposed bridge response systems under

different earthquake records is steamied, and the response of different bridge systems is compared. In this case, it is important to investigate the self-reversible effect on the SMA-LRB separators and to reduce the residual displacement effect on the separators and also because of the significant effect of shear forces on the V-shaped bridges, the effect of these separators on the reduction of forces The 3 ton bridges will be evaluated.

6-1- Earthquake Records

A set of three natural and synthetic earthquake acceleration based on the soil type of site C (factor coefficient $S = 1.5$) were used in this study to perform a time history analysis whose information is presented in the table (2) is brought. In this case, in order to investigate the effect of earthquake orientation on bridge structure, the 1999 near Chi-Chi Taiwan earthquake record was used and one station is specified in Table (2). In this case, a study by Becker in 2007 [18-20] will be used to separate the pulse effect of earthquake orientation and study this effect on the bridge structure [18-20], based on this research and the use of the present program in Matlab software the pulse direction effect values will be extracted from the earthquake record as shown in Figure 6.

Table 2: Characteristics of the records examined.

Seismic.No	Origin/Earthquake	PGA (g)	Duration (s)	Time steps (s)	Scale
1	Northridge-Baldwin	1.1	60	0.02	$\gamma_1 \cdot 0.35 \text{ g}$
2	SIMQKE-Aritif.1	0.6	19.19	0.1	$\gamma_1 \cdot 0.35 \text{ g}$
3	ChiChi-TCU052N	220.6	90	0.1	$\gamma_1 \cdot 0.35 \text{ g}$

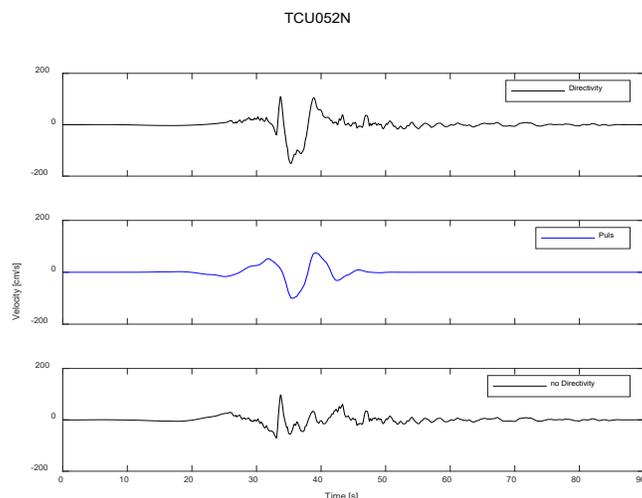
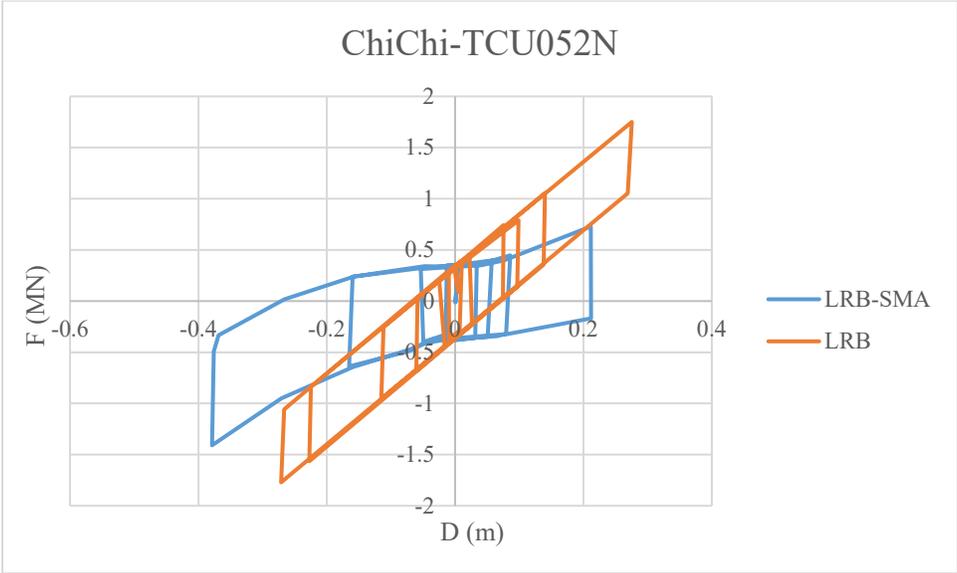
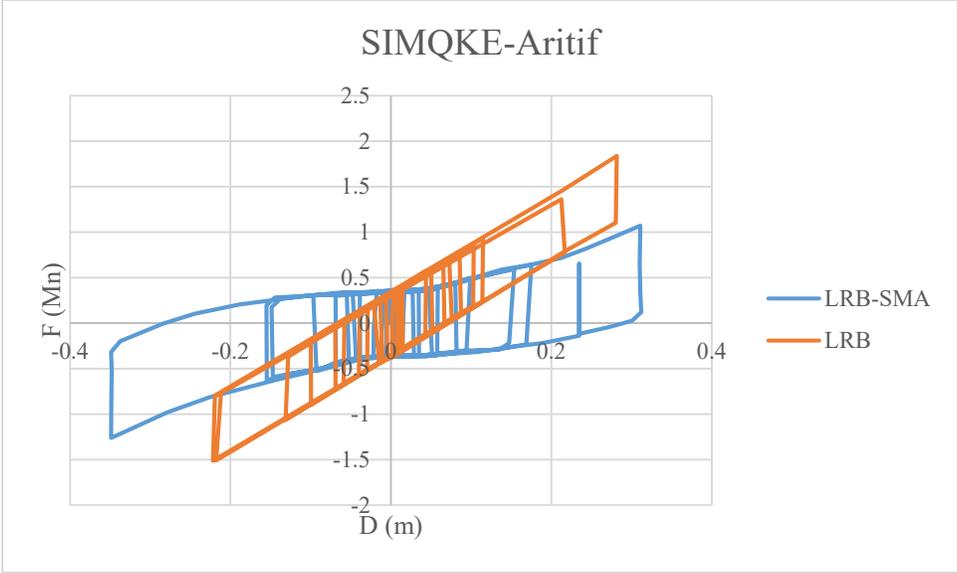


Figure 6: Record of Chi-Chi earthquake with direction pulse extraction.

7. Check the results

According to the cases presented below, the desired bridge in two LRB and SMA-LRB separator modes optimized for SMA values falls under the reported earthquake records. In one of these records the effect of earthquake orientation is taken into account in order to compare the effect of this effect on the two desired separators at the junction of the bridge. In one of these records the earthquake orientation effect is taken into account. It is possible to compare the significance of this effect on the two separators desired at the junction of the bridge.

Considering the importance of the forces created at the piers of the bridge and especially the values of shear force at these piers after evaluating the time history result of the desired analysis of the maximum stress values at the pier of the bridge and the displacement in the separators evaluated And it will be analyzed because the intended joint displacement is also of great importance for the overall stability of the structure. Initially, the results of the hysteresis diagrams of the two separator models will be examined.



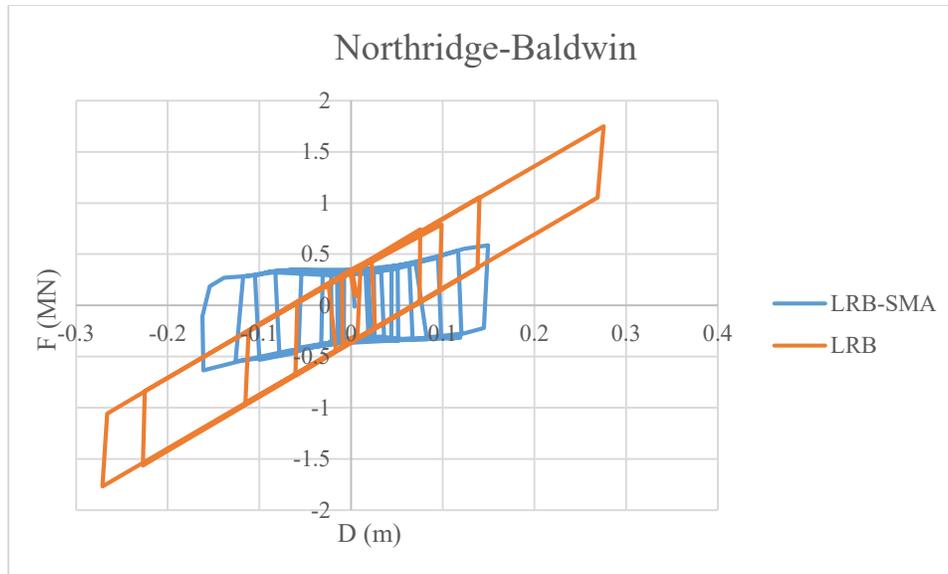


Figure 7: Results of the bridge hysteresis investigated under the presented records.

According to the results of the hysteresis diagrams, it can be seen that the bridge equipped with the LRB-SMA separator in the substructure connections to the superstructure with less force tolerance. This means that the bridge in question has a greater ability to withstand seismic forces has a higher level of energy absorption and this means that the desired bridge has a greater ability to withstand seismic forces, which will increase the seismic response of structures. It will also have a permanent displacement due to the earthquake record with the LRB separator directionality effect and will no longer be able to return to its original state, which this will increase the seismic damage to the piers of the bridge as well as repair costs. In the following we can see the results of acceleration and displacement time history for the desired records.

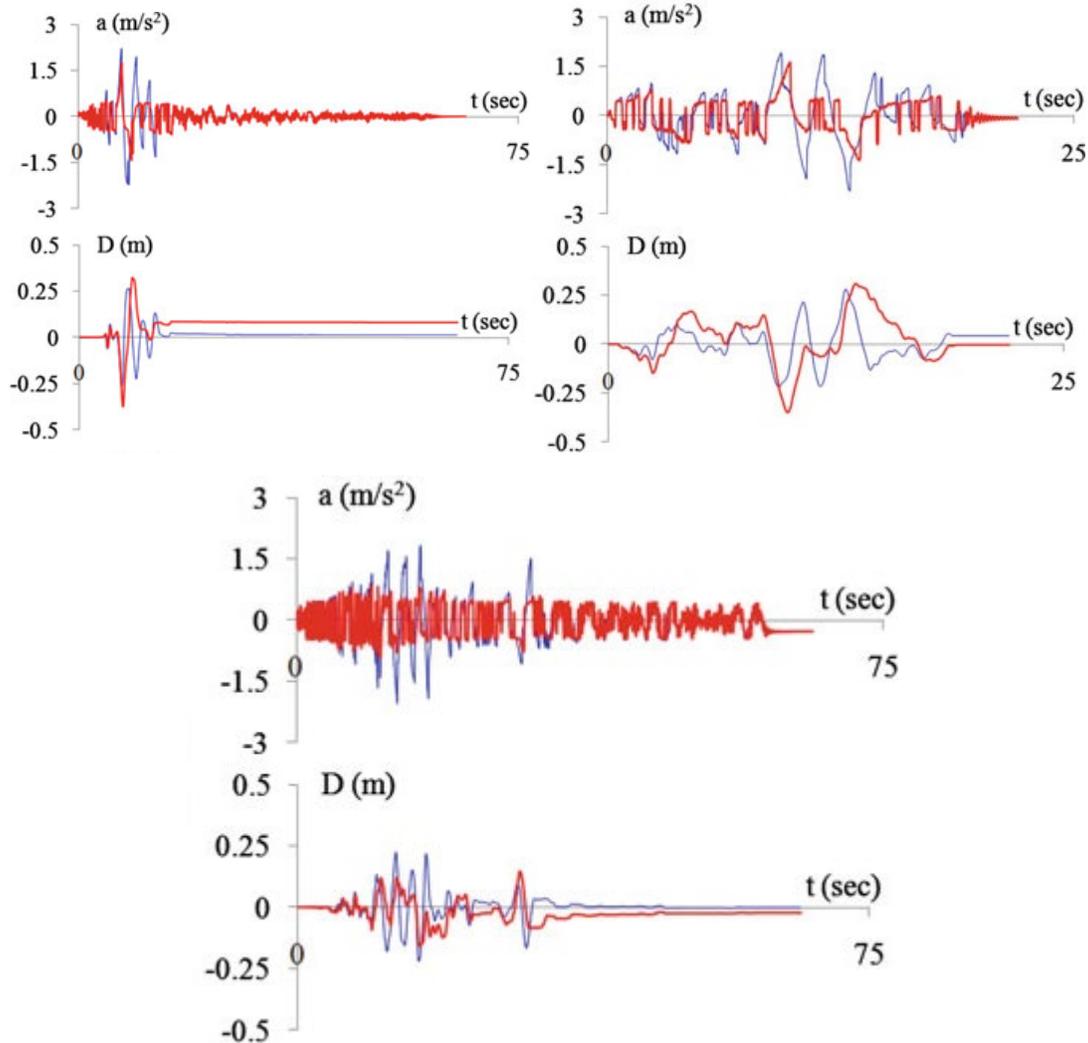


Figure 8: Acceleration and displacement time history of the investigated bridge under the presented records.

According to Fig. 8, it can be seen that if there are directional pulses in earthquakes due to the sudden force applied to the connection system in the structure, if using the usual classical systems it is possible to have permanent displacement in the separators. Because the previous systems used only a single lead core, and the plastic displacement created in it would remain a residual displacement in the system. It increases the displacement in the desired system and consequently increases the forces applied to the structure, because in this case, the system did not work properly and will not dissipate energy applied to structures. Given the significant importance of shear forces on V-shaped bridges in Table 3, the maximum displacement, velocity, acceleration, and shear force applied to the structural foundations (piers) can be seen.

Table 3: Characteristics of the records examined.

Seismic.No	D _{max} (m)		V _{max} (MB)		a _{max} (m/s ²)	
	LRB	SMA-LRB	LRB	SMA-LRB	LRB	SMA-LRB
1	0.350	0.281	1.6	0.6	2.0	0.9
2	0.159	0.227	1.8	1.1	2.2	1.8
3	0.375	0.267	1.75	1.01	2.3	1.6

According to the results presented in Table (3), it is observed that by using SMA-LRB separators in bridges system, the amounts of shear stresses at the pier of the bridge is significantly reduced and this increases the seismic bridge Parameters. Also, by reducing the shear forces at the pier of the bridge, the possibility of damage to the bridge is reduced and more economical sections can be used in the bridge structure.

8. Conclusion

The purpose of this study was to investigate the feasibility of using structural separators in V-shaped bridge joints and the effect of these joints in conditions where the bridge is under an earthquake record with directional pulse. Initially, three different configurations were investigated to evaluate the feasibility of integrating memory alloys that were recently introduced in the field of structural engineering, and according to optimization results based on genetic algorithm third Configuration and 15mm rod diameter was considered as the most optimal configuration to combine memory alloys with LRB separators. Further, by applying recordings with and without orientation effect to the bridge structure, it was observed that the SMA-LRB system with lower force tolerance, the amount of surface area absorbed more energy and this means that the desired bridge had a greater ability to withstand seismic forces. This has the potential to increase the seismic response of structure. Also, the earthquake record will have a permanent displacement with the LRB separator orientation effect and will no longer be able to return to its original state, which will increase maintenance costs if the SMA-equipped separator will return to its initial displacement due to the specific features of this material. It is also observed with respect to the results presented that the shear force values applied to the bridge piers is reduced by approximately 40% in all three records, which increases the capacity of the bridge structure to withstand seismic forces as well as reduce the damages to life and financial losses.

Reference

1. Seyyed Mahdi, Z. And S. Habib, Seismic performance evaluation of bridges with existing thermal expansion bearings.
- .2 Sarrazin, M., et al., Performance of bridges with seismic isolation bearings during the Maule earthquake, Chile. *Soil dynamics and earthquake engineering*, 201 :47 .3p. 117-131.
- .3 Lee, G.C., Y. Kitane, and I.G. Buckle, Literature review of the observed performance of seismically isolated bridges. *Research progress and accomplishments: multidisciplinary center for earthquake engineering research*, 2001: p. 51-62.
- .4 Monzon, E.V., et al. Seismic response of full and hybrid isolated curved bridges. in *Structures Congress 2012*. 2012.
- .5 Al-Anany, Y.M. and M.J. Tait, Experimental assessment of utilizing fiber reinforced elastomeric isolators as bearings for bridge applications. *Composites Part B: Engineering*, 2017. 114: p. 373-385.
- .6 Sanchez, J., et al., Static and dynamic stability of elastomeric bearings for seismic protection of structures. *Journal of structural engineering*, 2012. 139(7): p. 1149-1159.
- .7 Vayas ,I. and A. Iliopoulos, *Design of steel-concrete composite bridges to Eurocodes*. 2013: CRC Press.
- .8 Han, L., et al., Field and computational investigation of elastomeric bearings in high-demand steel girder application. *Journal of Constructional Steel Research*, 2019. 162: p. 105758.
- .9 Van Engelen, N.C., *Fiber-reinforced elastomeric isolators: A review*. *Soil Dynamics and Earthquake Engineering*, 2019. 125: p. 105621.
- .10 Eröz M., D.o., *A Comparative Assessment Of Sliding And Elastomeric Seismic Isolation In A Typical Multi-Span Bridge*. *Earthquake Engineering*,, 2013. 17: p. 637–657.
- .11 Shiravand, M. and M. Rasouli. Effects of substructure mass participation on natural period of multi-column base isolated bridges. in *Structures*. 2019. Elsevier.
- .12 E. Choi ,T.N., JT Oh, *An isolation bearing for highway bridges*

using shape memory alloys. *Materials Science & Engineering*, 2006. 438(1): p. 1081-1084.

.13 Hurlebaus, O.E.O.a.S., Seismic assessment of bridge structures isolated by a shape memory alloy/rubber-based isolation system. *Smart Mater. Struct.*, 2011. 20(1): p. 15003.

.14 Dolce, M., D. Cardone, and R. Marnetto, Implementation and testing of passive control devices based on shape memory alloys. *Earthquake Engineering & Structural Dynamics*, 2000. 29(7): p. 9.968-45

.15 Corbi, O., Shape memory alloys and their application in structural oscillations attenuation. *Simulation Modelling Practice and Theory*, 2003. 11(5-6): p. 387-402.

.16 Auricchio, F., D. Fugazza, and R. Desroches, Earthquake performance of steel frames with nitinol braces. *Journal of Earthquake Engineering*, 2006. 10(spec01): p. 45-66.

.17 Qiu, C. and L. Tian, Feasibility analysis of SMA-based damping devices for use in seismic isolation of low-rise frame buildings. *International Journal of Structural Stability and Dynamics*, 2018. 18(06): p. 1850087.

.18 Tothong, P., C.A. Cornell, and J. Baker, Explicit directivity-pulse inclusion in probabilistic seismic hazard analysis. *Earthquake Spectra*, 2007. 23(4): p. 867-891.

.19 Shahi, S.K. and J.W. Baker ,An empirically calibrated framework for including the effects of near-fault directivity in probabilistic seismic hazard analysis. *Bulletin of the Seismological Society of America*, 2011. 101(2): p. 742-755.

.20 Baker, J.W., Quantitative classification of near-fault ground motions using wavelet analysis. *Bulletin of the Seismological Society of America*, 2007. 97(5): p. 1486-1501.