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Research Article

Seismic fragility evaluation of box deck concrete bridge equipped with shape memory alloy under bi-directional earthquake loading

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ABSTRACT

Bridges are one of the most important elements of the transportation system in all countries. The collapse of a bridge or the time required for the repair of a damaged bridge can lead to traffic disruption and relief operation suspension that in turn results in the increased earthquake cascading tertiary effects. Therefore, reducing the vulnerability of bridges has always been the focus of engineers. The use of shape memory alloys (SMA) is one of the new solutions that have been presented and received attention in this field. The purpose of this research is to investigate the effects of using SMAs on the seismic behavior of straight box deck concrete bridges. For this purpose, a typical box deck concrete bridge is considered, and in the area of the plastic hinges of the bridge piers, the longitudinal steel bars are replaced with nickel-titanium SMA bars. The studied bridge is analyzed in two cases with and without the use of SMA under the effect of 3 categories of acceleration time histories, consisting of 120 strong ground motion records. Finally, the fragility curves for the maximum drift ratio and residual drift ratio values are calculated. The results show that the use of nickel-titanium SMA bars increases the maximum drift ratios and reduces the residual drift ratios. In this way, the permanent deformations will be decreased.

Keywords: nickel-titanium shape memory alloy (Nitinol); concrete bridge box deck; bridge failure modes; probabilistic earthquake demand model

1. Introduction

Earthquakes can have disastrous consequences for society and the economy. In most countries, the highway transportation network includes numerous bridges with different geometry and materials, the construction of most of which dates back to the years before the development of advanced seismic codes. Clearly, due to the lack of sufficient knowledge and lack of proper implementation at that time, they are vulnerable to earthquakes. Therefore, it is necessary to assess the seismic vulnerability of the existing bridges and determine the damage level of the bridge structure caused by the earthquake[1]. The results of these

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analyses may indicate the need for the rehabilitation or renewing these bridges. In this way, reliable documents are provided for the huge cost of bridge rehabilitation.

Existing seismic vulnerability methodologies have tended towards structural fragility curves in recent years. A fragility curve is a suitable tool for estimating the failure limit states of the bridge, which expresses the conditional probability of reaching a failure limit state or exceeding it as a function of ground motion parameters. These types of curves are very useful both for bridges in the current situation and for rehabilitated bridges. Reliable fragility curves for retrofitted bridges have made it possible to evaluate various methods of retrofitting on the seismic performance of bridges and bridge design.

In order to reduce earthquake forces, special materials or connections can be used. The use of shape memory alloy (SMA) connections is one of the methods used to reduce the vulnerability of bridges[2]. SMAs, which are known as smart materials, have unique advantages and characteristics compared to conventional energy-consuming systems, including the lack of need for replacement after an earthquake, high resistance to corrosion and fatigue, and high energy consumption capability. The most famous shape memory alloy, used in this research, is Nitinol, which is a combination of nickel and titanium. The main characteristic of these materials is their superelastic behavior, which means that they can withstand large strains up to about 10%, without creating residual strain. Billah et al. (2022) provideed a comprehensive overview of how SMAs can mitigate structural damage during seismic events, emphasizing their role in creating resilient infrastructure[2]. Their review highlights various methodologies for integrating SMAs into bridge designs, showcasing their ability to recover from deformations and limit residual displacements after earthquakes. Qiang et al. (2022) focus on the advancements in Fe-based SMAs specifically for the rehabilitation of reinforced concrete bridges. They discuss how these materials can extend the service life of existing structures by enhancing their mechanical properties and providing self-healing capabilities[3]. The rview emphasizes the effectiveness of SMA applications in reducing maintenance costs and improving safety, particularly in aging infrastructure. Vůjtěch et al. (2025) further illustrate the practical application of iron-based SMAs in strengthening deficient steel-concrete composite bridges. Their study demonstrates successful implementation strategies that not only improve load-bearing capacities but also enhance structural monitoring through integrated SMA systems[4]. Wang et al. (2024) suggested that SMA can effectively manage thermal stresses while maintaining structural integrity under varying load conditions[5]. Qian et al. (2024) contribute to this discussion by reviewing the mechanical properties and self-healing capabilities of SMAs in concrete applications. They provide insights into hybrid composite fabrication techniques that enhance the performance of concrete structures under dynamic loading conditions. This research highlights the versatility of SMAs in modern construction practices[6].

DesRoches and Delemont (2020) investigated the seismic rehabilitation of bridge piers with SMA. In their models, the abutment and intermediate piers of the bridge were equipped with SMA fasteners. Their results showed that the use of SMA fasteners in the abutment and piers of the bridge reduces the maximum relative displacement[7]. Billah and Alam (2013) reinforced the base of the bridge piers in the plastic hinges area with SMA and the remaining part with ordinary steel bars. The result of this study showed a high reduction in bridge foundation damage in the case of using SMA compared to ordinary steel bars[8]. Shrestha and Hao (2015) conducted a parametric study of the seismic performance of bridge foundations with SMA connections, comparing residual displacements in reinforced concrete with SMA and reinforced concrete with rebar. The results of this study showed that the residual displacements in reinforced concrete with SMA were much less compared to steel reinforced concrete[9]. Zheng et al. (2018) evaluated the life cycle performance and flexibility of continuous reinforced concrete bridges with SMA braces. The results of the study indicated that the bridge's seismic performance, life cycle, and flexibility are significantly improved with SMA braces[10]. Despite such results due to the variety of bridges around the world, it is not possible to evaluate the damage of different highway bridges with only one method. Concrete box deck bridges are one of the types of highway bridges that are designed to cross certain obstacles and are built directly or with different arc radii.

This research evaluates the efficiency of using SMA connections in straight box deck concrete bridges and examines their performance. To this end, the seismic performance of straight concrete box deck bridges, and fragility curves are calculated in different damage states. Nonlinear time history analysis is a reliable method to generate fragility curves. In this research, the bridge was analyzed in two cases with and without SMA under 120 ground motion records. In order to extract the fragility curves of the bridge, the probabilistic earthquake demand model is used and the values of the maximum drift ratio and residual drift ratio of the columns are considered as engineering demand measures (DM). Fragility curves are calculated for four failure modes: miner, moderate, high, and complete failure, and the effectiveness of using SMA is investigated.

2. Characteristics of the studied bridge

To investigate the seismic behavior of the bridge, a straight box deck concrete highway bridge is considered. To simulate the seismic behavior of the bridge, OpenSees software is used for the 3D modeling of the bridge[11,12]. The bridge deck width is 36.5 meters, the length of each 4 spans is 23.97 meters, and the height of all columns is 5.46 meters. The bridge elevation view is shown in **Figure 1**. We study two bridge models in two cases with and without SMA. In the finite element model, the behavior of the bridge superstructure is considered linear using the ElasticBeamColumn element. The modeled bridge has 3 bases and 4 columns. In the modeling of the columns, the P-Δ effect and column twisting are included to determine the deformation of the column cross-section. In the considered bridge class the top of the column has a rigid connection to the deck. The box section, and Fiber elements are used to model the circular column section. It includes a concrete cover (unconfined concrete), concrete core (confined concrete), and steel bars. Displacement-based beam-column element with extended plasticity method has been used for nonlinear modeling of bridge columns. In this model, Concrete07 is used for the concrete cover and core, and Steel02 is used for the steel modeling[6]. The yield strength of steel bars is 404 MPa. The details of the modeling of the cross-section (Elevation view and Plan view)of the bridge foundations are shown schematically in **Figure 1** and **Figure 2**, respectively.

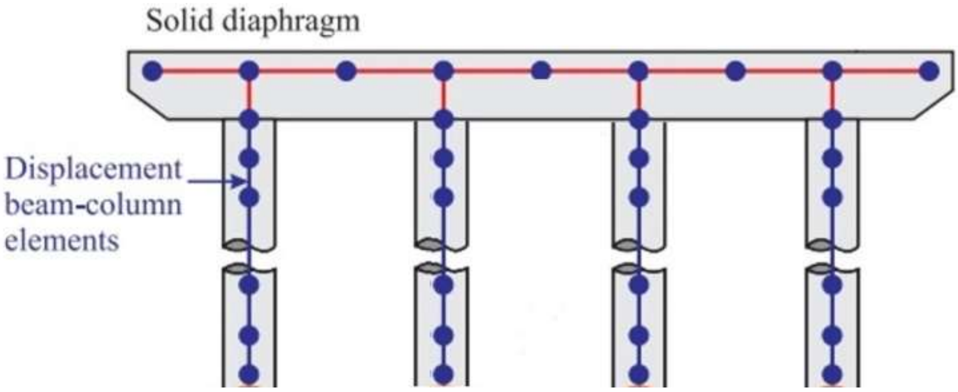

Figure 1. Cross-section (Elevation view) of the bridge.

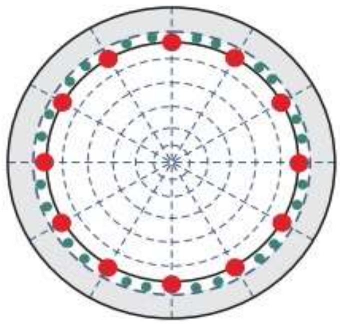

Figure 2. Plan view of the bridge pier.

As mentioned before, in the models with SMA, steel bars are replaced by SMA bars in the area of the plastic hinges of the column. To simulate the behavior of SMA bars, the Self Centering behavioral model was used, the parameters are shown in **Table 1**[13]. The stress-strain curve of the behavioral model of the SMA is shown in **Figure 3**.

Table 1. Parameters of SMA bars.

Parameter	**value**
Modulus of elasticity, E	62.5(GPa)
Austenite to martensite finishing stress, f_{p1}	510(MPa)
Austenite to martensite starting stress, f_y	410(MPa)
Martensite to austenite starting stress, f_{T1}	370(MPa)
Martensite to austenite stress, f_{T2}	130(MPa)
Maximum superelastic strain, ε_s	6(%)

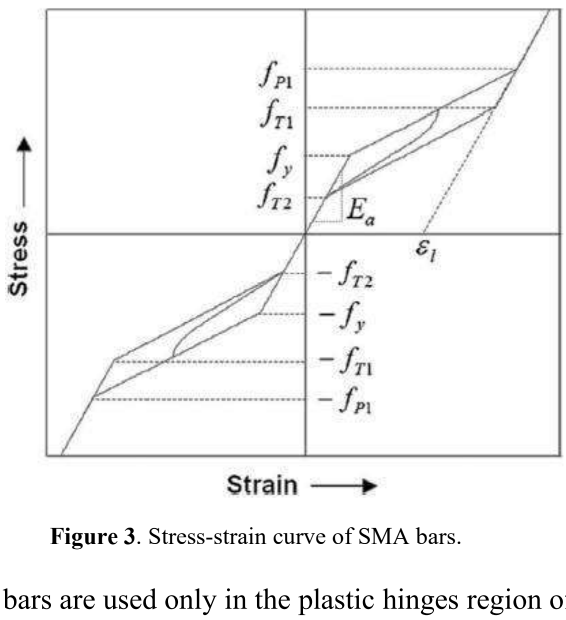

Figure 3. Stress-strain curve of SMA bars.

As mentioned before, SMA bars are used only in the plastic hinges region of the columns (bridge piers). The plastic hinge length of columns is estimated based on equation (1) [14]:

$$L_P = 0.08L + 0.002 \times d_b \times f_y \quad (1)$$

where L_P is the length of the plastic hinges, L is the height of the bridge column, d_b is the diameter of the steel bar, and f_y is the yield stress of the steel. The height of the bridge column is 5.46 meters, the diameter of the bar is 0.043 meters and the yield stress of the steel is 404 MPa, so, the length of the plastic hinges is 0.82 meters. As mentioned before, the considered bridge class has a rigid connection to the deck at the top of the columns to the box section. The simple connection of the column to the footing reduces the moment on the footing and leads to the formation of a plastic hinge only at the top of the column.

3. Record selection

The bridge considered in this research has the specifications of bridges built in California, America. Therefore to evaluate the seismic behavior of this bridge from a set of 120 records provided by Baker et al. [9]. They proposed this set of accelerograms for seismic analysis of bridges located in the state of California using the Conditional Mean Spectrum (CMS) method[15,16]. It should be noted that the selection of records based on the CMS method requires consideration of an earthquake scenario, including the magnitude, the site-to-fault distance, and the condition of the building. Baker et al. considered three different scenarios for record selection. The selected accelerograms are presented in three different categories that their characteristics are presented in **Table 2**.

Table 2. Acceleration records information.

category	Shear wave velocity (m/s)	Soil type	Distance (km)	Magnitude (Mw)
1	200-400	soil	10	7
2	250	soil	25	6
3	625	rock	10	7

The two horizontal components of these accelerograms are applied together in two perpendicular directions to the bridge model, and the time history analyses response are used to calculate the fragility curve[17]. It should be noted that the application of this number of real earthquake records can partially take into account the effects of uncertainty in the earthquake on the final responses.

4. Fragility curves

The most accurate analytical method for calculating the fragility curves of bridges is the use of nonlinear dynamic time history analysis to determine the seismic demand. The results of this type of analysis are highly sensitive to the selected earthquake records, so a large number of earthquake records should be considered in the analysis to prepare fragility curves. In this research, as mentioned before, 120 different records were used. By using the fragility curves, it is possible to relate the parameters of the earthquake intensity criteria to the engineering seismic demand parameters. The engineering seismic demand parameter is a response of different bridge elements that can be used in damage estimation. In general, fragility can be expressed as a conditional probability function as:

$$\text{Fragility} = P[(\text{EDP} - \text{C} \geq 0)|\text{IM}] \tag{2}$$

where EDP is the seismic demand parameter, C is the capacity parameter, and IM is the earthquake intensity measure. Therefore, it can be seen that seismic fragility is obtained by combining demand and capacity models. Based on the method presented by Cornell et al.[10], using the linear regression between the logarithm of the earthquake IM and the structural response, the probabilistic seismic demand model can be shown as:

$$\ln(\text{EDP}) = \ln(a) + b.\ln(\text{IM}) \tag{3}$$

where a and b are regression coefficients.

By finding an estimate of the mean of the seismic demand, the variance of the seismic demand for a value of the earthquake IM, ($\beta_{(EDP|IM)}$) can be obtained as:

$$\beta_{EDP|IM} = \sqrt{\frac{\sum_{i=1}^{n}[\ln(EDP_i)-(\ln a+b\ln IM_i)]^2}{N-2}} \quad (4)$$

where N is the total number of applied records. In the current research, the maximum drift ratio and residual drift ratio of columns are considered as engineering seismic demand measures. Also, peak ground acceleration (PGA) has been selected as the IM [18,19].

Determining the capacity or limit states of different members of bridges is another essential part in calculating the seismic fragility of bridges. Nielson (2005) developed limit states for a wide range of bridge elements[20]. Assuming a log-normal distribution, each limit state can be expressed with a median parameter S_c and a varance parameter β_C for the distribution of different states of components damage[21-23]. The limit state for each of the components of the bridge can be expressed using a standard lognormal cumulative distribution function, whose variance and median values can be calculated using equations (6) and (7), respectively.

$$\xi_C = \frac{\sqrt{(\beta_{EDP|IM})^2+(\beta_c)^2}}{b} \quad (6)$$

$$\lambda_c = \exp\left(\frac{\ln(S_c)-\ln(a)}{b}\right) \quad (7)$$

where, $\beta_{(EDP|IM)}$ and β_C are the logarithmic standard deviation of demand and capacity, respectively. The parameter values related to the failure limit states of the bridge columns considering the maximum drift ratio and residual drift ratio are presented in **Tables 3** and **4**[24-28].

Table 3. Parameters of the limit states of the bridge piers with SMA for maximum drift ratio and residual drift ratio.

	Maximum drift ratio		**Residual drift ratio**	
limit states	S_c	β_c	S_c	β_c
DS-1	0.28	0.21	0.33	0.21
DS-2	1.68	0.26	0.62	0.26
DS-3	2.66	0.43	0.87	0.43
DS-4	5.05	0.50	1.22	0.50

Table 4. Limit state parameters of bridge foundation without SMA for maximum drift ratio and residual drift ratio.

	Maximum drift ratio		**Residual drift ratio**	
limit states	S_c	β_c	S_c	β_c
DS-1	1.41	0.22	0.25	0.25
DS-2	2.75	0.24	0.75	0.25
DS-3	3.90	0.22	1.00	0.46
DS-4	5.00	0.18	1.50	0.46

The results of the nonlinear dynamic analysis are used as the seismic demands of the members. By applying an earthquake to the bridge, the response of different members that affect the vulnerability of the bridge is recorded. In this framework, the seismic demand and the capacity of the structure follow the log-normal distribution, and the fragility of the members is obtained as:

$$p[EDP > C|\, IM] = \varphi\left[\frac{\ln\frac{IM}{\lambda_c}}{\xi_c}\right] \quad (8)$$

5. Results and discussions

The time history analysis results for the bridge models, subjected to 120 earthquake records, were obtained to evaluate the seismic performance of the structures. The maximum drift ratio and residual drift ratio responses of the columns were analyzed to calculate the fragility curves, which are presented in **Figures 4** to **7**.

A comparison of **Figures 4** and **5** reveals that incorporating Shape Memory Alloy (SMA) hinges into the bridge design results in an increase in the maximum drift response. This increase leads to a higher probability of damage in the limit state of minor damage. While this finding may raise concerns regarding immediate structural integrity, it is important to note that the increase in damage probability for more severe limit states is relatively minor and, in some cases, negligible. This suggests that while SMA hinges allow for greater flexibility during seismic events, they do not significantly compromise the overall safety of the structure under extreme conditions.

In contrast, **Figures 6** and **7** illustrate a compelling advantage of using SMA joints: a significant reduction in the probability of failure when considering residual drift ratio as a parameter of engineering seismic demand. The reduction in residual drift is particularly noteworthy because it indicates that structures equipped with SMA hinges experience less permanent deformation after an earthquake. This characteristic is critical for maintaining the long-term functionality and safety of bridges. The ability of SMA materials to return to their original shape after deformation means that even though the maximum drift may be higher, the structure can recover more effectively from seismic events. This results in lower residual displacements, which are crucial for ensuring that bridges remain operational post-earthquake. The findings suggest that while SMA hinges may allow for greater initial movement during seismic activity, they ultimately contribute to enhanced resilience by minimizing long-term damage.

The results shows that the use of SMA hinges increases the maximum drift ratio and associated damage probabilities under certain conditions, their impact on reducing residual drift ratios highlights their effectiveness in limiting permanent deformations. This dual behavior underscores the potential of SMA technology to improve both immediate performance during seismic events and long-term structural integrity, making them a valuable asset in modern bridge engineering.

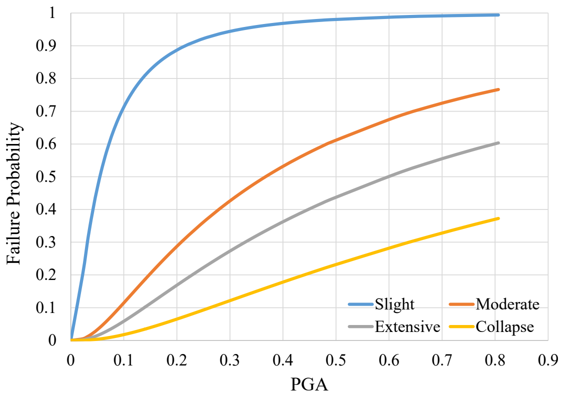

Figure 4. Fragility curves for the bridge with SMA considering the maximum drift ratio.

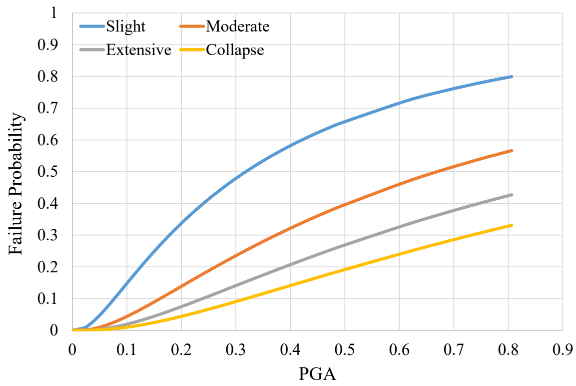

Figure 5. Fragility curves for the bridge without SMA considering the maximum drift ratio.

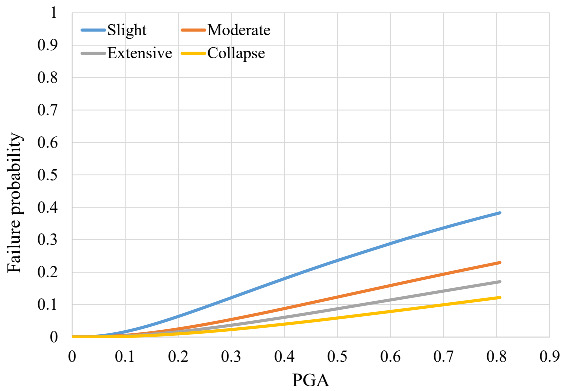

Figure 6. Fragility curves for a bridge with SMA considering residual drift ratio.

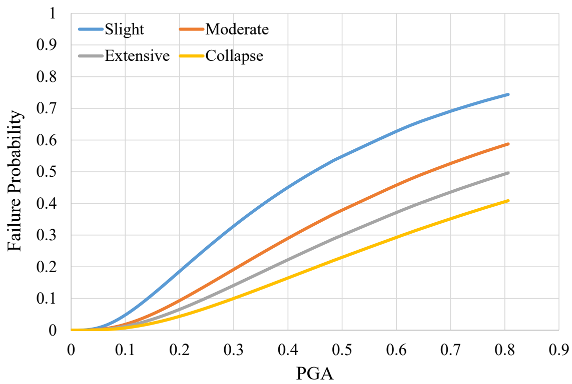

Figure 7. Fragility curves for a bridge without SMA considering residual drift ratio.

6. Conclusion

In this research, the effects of using SMA bars in the plastic hinge regions in box deck concrete bridges were investigated. For this purpose, two nonlinear models of a highway bridge with and without memory shape alloy were developed and nonlinear time history analysis was performed under the effect of 120 earthquake records. Finally, to evaluate the effects of using these systems, fragility curves were calculated for four different failure limit states.

The obtained results showed that if the maximum drift ratio is considered, the use of SMA in the studied bridge causes an increase in the maximum drift ratio and consequently an increase in the probability of failure. Also, by considering the residual drift as a parameter of seismic engineering demand, unlike the maximum drift, the probability of failure in different situations is reduced, and this means that the use of these connections reduces the permanent deformations in the bridge columns. In other words, although the existence of SMA hinges increases the maximum drift ratio experienced during an earthquake, if the bridge does not collapse due to an earthquake, after the earthquake, plastic deformations will remain much less in the structure, which is a desirable issue.

In summary, while SMA hinges may increase the maximum drift experienced during an earthquake, they significantly mitigate permanent deformations if the bridge remains standing post-event. This characteristic is particularly advantageous, as it enhances the overall resilience and longevity of the structure.

Conflict of interest

The authors declare no conflict of interest.

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