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FRAGILITY MODELING AND COST BENEFIT ANALYSIS OF AN SMA ENHANCED BRIDGE EXPANSION JOINT

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Abstract

This work demonstrates through fragility modeling and cost benefit analysis, how a shape memory alloy (SMA) enhanced modular bridge expansion joint (MBEJ) offers long-term benefits to a bridge system. An SMA enhanced MBEJ aims to reduce joint system failure during an earthquake that would otherwise lead to damage and limiting of bridge functionality post event. Two levels of large capacity MBEJs exist: seismic and service joints. During an earthquake, service joints are often assumed to fail, requiring costly road closures and joint system replacement. For regions where a service joint is typically required, but where earthquake risks exist, this SMA enhanced MBEJ can be an alternative. One advantage of Nickel Titanium SMAs is that they exhibit 8-10% recoverable strain elongation which, when the material is formed to a compact size and shape, offers the MBEJ improved performance without significantly altering its mechanical configuration. This enhanced MBEJ uses an SMA spring placed in-series with existing MBEJ components to increase displacement capacity without modifying the service level performance. Though such joints are often neglected in bridge analysis, in order to gauge the benefit and impact of the SMA enhancement over a baseline system, an expansion joint model is placed in a representative bridge model, characteristic of one that incorporates large capacity MBEJs. This bridge model, when subjected to a suite of ground motions, captures the MBEJs response, which is used to generate unique component fragility curves that describe their failure probability if a ground motion intensity is realized. Looked at over 25, 50 and 75 year time intervals in specific regions of the United States, a cost benefit analysis shows that investment in the SMA enhanced MBEJ system can be worthwhile.

Keywords: Fragility curves, Expansion joints, Cost benefit assessment, SMA.

1. Introduction and Literature Review

Shape memory alloys (SMAs) are used in a variety of state-of-the-art and established applications ([1-10]). Within different science and engineering disciplines, target uses vary; but all seek to exploit unique SMA behaviors that meet a need through material rather than mechanical contrivance. Shape memory alloys, and specifically for this work nickel-titanium alloys, exhibit 8-10% recoverable strain elongation ([11-13]). The superelasticity effect enables this elongation behavior, an effect which describes the rearrangement of atoms in the material's crystal structure instead of the breaking of atomic bonds. Within earthquake applications, the ability to elongate and return to an original shape with minimal component damage is advantageous for limiting repair work and costs, reducing the offline time of networks and lifeline systems, and safeguarding the public. Presented in this study is the assessment of the long term benefits of a shape memory alloy enhanced modular bridge expansion joint (MBEJ), which is modeled in a multi-span bridge and then subjected to a suite of ground motions in order to capture the response of individual components and compare that performance to a non-enhanced scenario.

Modular bridge expansion joints are accordion-like systems that open and close with differential displacement between adjacent bridge decks. Service level MBEJs accommodate movement parallel to the direction of traffic, mostly associated with annual thermal fluctuations and traffic induced vibrations [14]; while seismic level MBEJs accommodate movement in multiple degrees of freedom [15]. The former joint type is assumed to fail during seismic events while the latter can be cost prohibitive and mechanically complex for more moderate level earthquakes. The lack of an intermediate level expansion joint, motivated investigation and development of an SMA enhanced MBEJ to improve a service level joint's seismic performance [16]. Through experimental testing, the enhanced joint was shown to prevent failure at differential displacements that caused failure in the service level configuration. The computer model development by [17] is used herein to determine the benefit beyond limited experimental testing, focusing on the performance under a range of estimated seismic hazards for moderate seismic regions.

Expansion joints are not typically included in the assessment of bridge performance during seismic events since they are not structural elements and are generally assumed to fail unless designed as a seismic expansion joint. Their inclusion here, and specifically the comparison between an enhanced and non-enhanced configuration, demonstrates how their post event functionality can impact bridge lifetime costs.

Derivation of cost benefit ratios follows [18], in which the authors developed an integrated approach to life-cycle costs and cost benefit analysis for seismic retrofit alternatives in bridges. Seismic hazard models and fragility curves for baseline and upgraded systems, looking at a range of damage states and up front and long term costs, facilitate risk-wise decision making. Modular bridge expansion joint fragility curves and MBEJ limit states are introduced herein, variables necessary for estimation of life-cycle costs.

The methodology for life-cycle cost analysis requires fragility estimates for the components being assessed which in turn requires knowledge of limit states. First this paper will present limit states derived from performance objectives developed by [17], in which the authors defined seismic level displacement capacities for service level MBEJs. These limit states are described below. A nonlinear time history analysis supplies component demands. When compared to capacities, MBEJ component fragility curves result. The methodology followed for the subsequent development of the cost benefit ratios is then described, with assumed costs.

2. SMA Enhanced MBEJ

A standard modular bridge expansion joint comprises a series of moving parts that combine friction forces with material resistance to facilitate movement. Two adjacent steel beams are cast into bridge deck segments with embedded anchor rods supplying positive connectivity to the bridge deck. Running parallel to the direction of traffic are support bars that transfer traffic loads to the bridge deck. Center beams sit on these support bars and via friction surfaces slide along the support bars when the joint opens and closes. Spacing between center beams is achieved through polymer equidistant devices that compress when the expansion joint opens and decompress when the joint closes. Therefore as the joint continues to open, the friction resistance between the center beams and support bars, in addition to the reaction force in the compressing polymer devices, resists joint opening. The polymer equidistant device in a standard MBEJ accommodates service level movements, however during seismic movements, the reaction force in the compressed polymer exponentially increases, inducing failure in the metal plates that hold the polymer in place [16]. An SMA spring in series with the equidistant devices, aims to maintain service level performance and trigger additional capacity during seismic level displacements. Figure 1 shows the standard and enhanced configurations for the equidistant devices used in this work.

Figure 1 (Left) Standard equidistant configuration, (Right) SMA spring in series with polymer equidistant device [16]

3. Limit States

Limit states are quantitative and qualitative descriptors of bounds between damage states. Bridge component limit states used in this work can be found in [19] and [20]. These are established limit states that describe typical damages found in slight, moderate, extensive and complete damage states. The quantitative limit states define lognormal distributions for each of the damage states, accounting for component uncertainties. These limit states also relate to post event repair times, i.e. the time before the bridge is returned to its pre-event level of functionality.

Limit states for modular bridge expansion joints reflect progressive failures triggered as the joint opens from completely closed through understood thermal displacement ranges and half again as much for theoretical seismic displacements [17]. The expansion joint damage states do not directly correspond to similar damage state nomenclature for bridges since, for instance, complete failure of the expansion joint does not signify complete failure in the bridge.

Modular bridge expansion joint limit states are shown in Table. The dispersions are assumed based on coefficient of variations (COV) following [20]. The dispersions are calculated from Eq. 1 following a lognormal distribution.

$$\beta = \sqrt{ln(1 + COV^2)} \quad (1)$$

Table 1 – Modular bridge expansion joint limit states

MBEJ Type	Slight		Moderate		Extensive		Complete	
	Med	Disp	Med	Disp	Med	Disp	Med	Disp
130mm polymer MBEJ (standard)	76	0.25	87	0.25	88	0.47	127	0.47
171mm polymer MBEJ (baseline)	76	0.25	108	0.25	114	0.47	178	0.47
SMA w/ 130mm polymer MBEJ	76	0.25	121	0.25	127	0.47	178	0.47

Units are in mm. Distributions are assumed to be lognormal with the Med = median value and Disp = dispersion (or lognormal standard deviation) of the distribution

The slight limit state is identical through each of the three expansion joint configurations because it relates to seal pull out and is a service level criteria held constant among the designs. Seals are rubber strips in the MBEJ that prevent water and debris from penetrating below the road surface. The moderate limit state is indicative of the beginning of yielding in the metal plates that hold the equidistant devices in place, while extensive damage relates to complete failure of these devices. Complete damage is related to yielding of the support bar restraining plates. Support bars are components that contribute to the structural integrity of the MBEJ and distribute traffic loads to the bridge decks. When support bars become dislodged they no longer support the center beams that run transversely to the bridge gap, and therefore the unsupported length of these center beams doubles when just one support bar fails. Fatigue and bending failure in the center beams can result, posing a threat to the safety of the public in addition to necessitating extensive repairs or replacement.

Two limit states relate to the metal plates because of their significance in the progression of failure, their importance in maintaining a safe surface across which traffic can pass and because of their relationship to the equidistant devices being supplemented with the SMA springs. The z-bar limit states relate to force limits that are translated into displacement limits for consistency with the slight and complete limit state prescriptions.

Because MBEJs are not meant to transfer large forces through the bridge decks, contributions from the joint to the dynamics of the bridge system and its components are expected to be minimal. When considering the functionality of the bridge however, the contributions of the MBEJ may be more significant.

4. Nonlinear Time History Analysis

A representative long span bridge is analyzed using Opensees [21], with a modular bridge expansion joint model [16] assigned between bridge segments. This expansion joint model describes each of the movable components within the system: polymer equidistant devices, friction devices, support bars, center beams, and bridge segments. The expansion joint model is modified to account for the Nickel Titanium SMA enhancement, whose material properties are taken from test data. Assuming a series system between the original expansion joint model and the SMA enhancement, the result is an increasing of the system’s displacement range with little increase in force until the SMA device reaches strain hardening. Two expansion joints of 229 mm capacity are used in a six span bridge, each span of 61 m. The bridge deck is supported on 23 m tall columns and uses high type steel expansion and fixed bearings representative of those used in older bridge types un-retrofitted with common elastomeric bearings. The bridge configuration in Figure 1 shows a bridge deck that is 20 m wide and therefore uses modular bridge expansion joints with 15 sets of equidistant systems spaced 1.2 m on center and 16 sets of support bars with associated friction connections, also spaced 1.2 m on center. The design details for the columns, abutments, bearings and deck follow that compiled by [20] for common non-seismically designed bridges in the region. These include for example the use of widely spaced transverse reinforcement (#13 bars spaced 305 mm o.c.) providing limited confinement in the concrete columns. A complete description of the bridge modeling methodology followed for the nonlinear time history analysis is presented in [20].

The Central Southeastern United States (CSUS) is taken as the seismic region, with 96 synthetic ground motions developed by Wen & Wu [23] and Rix and Fernandez [24] selected to simulate the seismic response of the bridge, as did Nielson [20] in his probabilistic seismic performance assessment of bridges in the CSUS. Ground motion records for other regions in the United States contain soil strata influences that differ from that in the CSUS, therefore synthetic ground motions were used because of a lack of earthquake records for this region [25]. Since the expansion joint model developed is focused on capturing longitudinal force deformation characteristics, the ground motion is therefore applied only in the longitudinal direction (i.e. the direction of traffic along the span of the bridge).

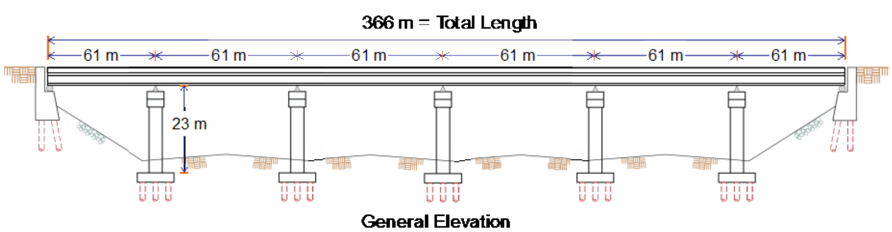


Figure 2a – Bridge configuration used in nonlinear time history analysis

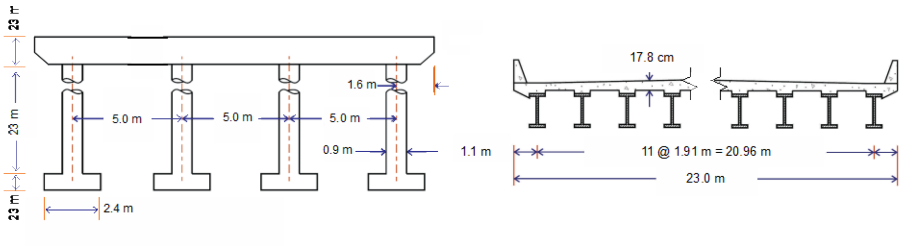


Figure 3b – Bridge configuration used in nonlinear time history analysis

Three different modular bridge expansion joint configurations are analyzed for comparison: 1) the service level configuration, which uses 130 mm long polymer equidistant devices and represents the most commonly installed single support bar configuration, and incidentally is the primary joint used for comparison with the SMA enhanced system 2) a baseline configuration, which uses elongated polymer equidistant devices measuring 171 mm in length, to see how simply adding displacement capacity using the existing components affects performance and 3) the SMA enhanced configuration which uses 76 mm long SMA springs in-series with standard length (130 mm) polymer equidistant devices. A schematic of the expansion joint plan view used in the case study bridge is shown in Figures 2a and 2b. The global joint response for the three joint configurations is shown in Figure 3.

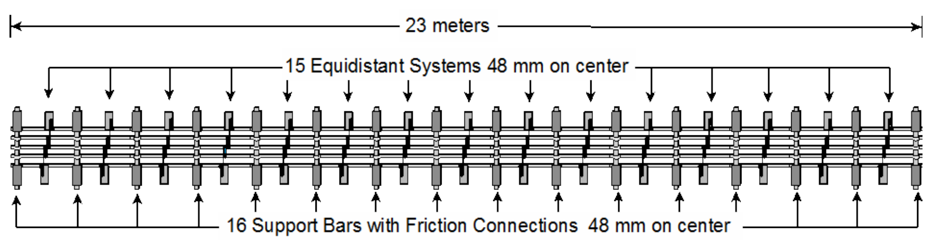


Figure 4 Underside of modular bridge expansion joint - 226 mm capacity joint and for a bridge deck 20 m wide

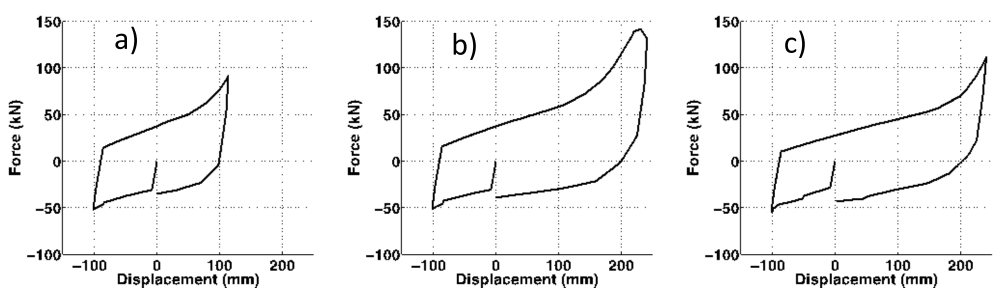


Figure 5 Global response for the three expansion joint configurations used in the nonlinear time history analysis: a) standard b) baseline c) SMA enhanced MBEJ, each with 15 sets of equidistant systems and 16 sets of friction systems

Within the following analysis, a worst case scenario for seismic events sets the initial gap prescribed for the expansion joints at the fully open position for service level displacements. This means that any additional opening immediately triggers the slight damage state in all the modular bridge expansion joint configurations, therefore this damage state is ignored in the subsequent presentation of results and discussions.

Throughout these analyses the seismic response of important bridge components, in addition to the expansion system, were monitored. These components include the columns, fixed and expansion bearings and the abutments. The deck is designed to remain elastic throughout the analysis. The output for the columns is related to column curvature, while for the other devices, element deformation is the monitored metric. Assessment of this output helps to show the influence, if any, of the included expansion system on those important bridge components. Force and displacement output are recorded for the expansion system as they both relate to damage states developed for the MBEJs.

5. Fragility Curve Methodology

Nonlinear time history analysis (NTHA) produces samples of the structural demand, which are used to derive probabilistic seismic demand models compared against established capacity estimates. NTHA is a method supported as being one of the most reliable means of obtaining the demand parameters, though it is computationally expensive [26].

The results from nonlinear time history analyses facilitate the generation of fragility curves, which are conditional probability statements of the likelihood of exceeding specified limit states for a component or system given the realization of an intensity measure. The general expression for a fragility is shown in Eq. 2.

$$Fragility = P[LS|IM = y] \quad (2)$$

where *LS* is the limit state (or damage level) of interest, *IM* is the intensity measure, which for example can be peak ground acceleration (PGA) or spectral acceleration at a given period, and *y* is the realization of the ground motion intensity measure selected. Typically the distribution of seismic demand and capacity of components are modeled with lognormal distributions [27] as further described below, leading to a closed form solution to the component fragility [28]:

$$P_f = \Phi\left[\frac{ln(S_D/S_C)}{\sqrt{\beta_D^2 + \beta_C^2}}\right] \quad (3)$$

where, S_C is median value of the structural capacity for the defined damage state, S_D is the median value of seismic demand, β_D is the lognormal standard deviation or dispersion of the demand, β_c is the lognormal standard deviation or dispersion of the capacity and $\Phi[\cdot]$ is the standard normal cumulative distribution function.

To compute the fragility curves, nonlinear time history analysis generates responses during the 96 seismic events for each of the three bridges utilizing different MBEJ configurations. The bridges used with each MBEJ configuration are identical. Using regression analysis, a linear fit through the log of the component demands results in a model whose values represent the medians of normal distributions for the components, if evaluated at each intensity measure magnitude. A power law assumption is used [29] and is shown in Eq. 4.

$$S_D = aIM^b \quad (4)$$

where, S_D is the seismic demand, *a* and *b* regression coefficients and *IM* is the intensity measure. This leads to the formulation of the probabilistic seismic demand models for the components as shown in Eq. 5. The standard deviation of the linear fit represents the dispersion of these distributions about their median values (Figure 4).

$$P[D \geq d|IM] = 1 - \Phi\left(\frac{ln(d) - ln(S_D)}{\beta_{D|IM}}\right) \quad (5)$$

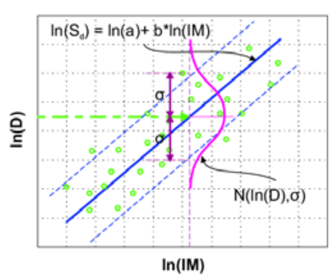


Figure 6 Probabilistic seismic demand model in transformed space [30]

Considering the limit state capacities for the bridge components and expansion joints and the respective probabilistic seismic demand models (PSDMs), the probability of limit state exceedance (component fragility) can be evaluated as shown in Eq. 6.

$$P[LS|IM] = \Phi\left(\frac{\ln(IM)-\ln(IM_m)}{\beta_{comp}}\right) \quad (6)$$

where, $ln(IM_m) = \left(\frac{\ln(S_c)-\ln(a)}{b}\right)$, β_{comp} is $\sqrt{\beta_{D|IM}^2 + \beta_C^2/b}$ and is the dispersion for the component fragility, S_c is the median of the capacity, $ln(a)$ is the intercept of the probabilistic seismic demand model (PSDM) and b is the slope of the regression line for the PSDM in the log space.

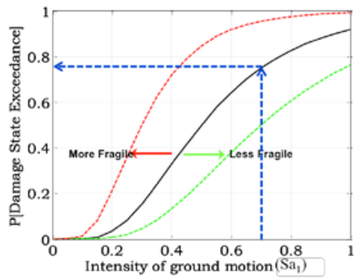


Figure 7 Representation of orientation for more and less fragile fragility curves [16]

6. Cost Benefit Methodology

A structure's life cycle costs (LCC) can be those up front and long-term costs associated with construction, maintenance and repair given damage. In this case however, focus is put on the lifetime costs associated with damage due to seismic events in order to measure the benefit of the SMA enhancement targeting this damage type. The difference in life cycle costs between two expansion joint configurations, for example the standard modular bridge expansion joint that uses 130 mm long polymer equidistant devices and the SMA enhanced system results, is a benefit (given a positive value). This benefit is then divided by the additional cost associated with use of the SMA spring, with the result being a cost benefit ratio (CBR) expressing the return on investment. In general when this ratio is greater than 1 the investment is worthwhile, however it should be acknowledged that there can be non-quantifiable benefits associated with an upgrade that may recommend investment although the cost benefit ratio is less than 1. These additional benefits may be indirect consequences of avoiding damage or repairs, avoiding increased traffic rerouting throughout the network, or including social and environmental impacts not quantified in the analysis.

This cost benefit analysis takes the probabilistic fragility curve models for the bridge components and convolves them with seismic hazard curves to determine, over a time interval, the benefit of investment. The methodology for obtaining the cost benefit ratios used here follows that presented in [18], which accounts for the direct economic losses associated with expected lifetime repair and replacement due to seismic bridge damage. The methodology utilizes a simplified approach to estimate indirect losses due to rerouting, though it does not include annual maintenance costs for bridge components given the emphasis on seismic LCC.

The annual seismic hazard curves, H(a), used in the life cycle cost benefit assessment come from the United States Geological Survey [31]. Hazard curves describe the mean annual frequency of exceeding different levels of seismic intensity for a particular location. The hazard curve for Paducah Kentucky, the location of the case study bridge, is shown in Figure 6, along with hazard curves for two other locations in the United States, Caruthersville Missouri and Charleston South Carolina. Though the bridge does not reside in these other locations, expansion joint performance under different seismic hazards offers insight into performance of the enhanced system and facilitates comparison of the dependency of the life cycle costs on the seismic hazard.

When considering a single bridge, and not a suite of bridge types, the spectral acceleration is often considered an appropriate intensity measure for assessment of bridge fragilities. For the bridge in this analysis, support of the 1-second spectral acceleration is additionally attributed to the fact that the bridge's natural frequency is approximately 1 sec and is not altered with inclusion or exclusion of the expansion joints. This intensity measure is therefore considered throughout the remainder of this work.

The hazard curves and the 1-second spectral acceleration fragility curves are used to evaluate the mean annual rate of exceeding a limit state, approximated as the annual failure probability:

$$P_{Af} = \int P[LS|Sa_1 = a] \left|\frac{dH(a)}{da}\right| da \qquad (7)$$

where, $H(a)$ represents the seismic hazard curve and $P[LS|Sa_1 = a]$ represents the fragility evaluated as a conditional probability of limit state exceedance given Sa_1. This mean annual frequency of exceedance is approximated by the mean annual probability for the infrequent seismic events presented here.

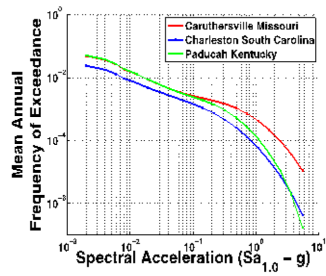


Figure 8 – 1 second spectral acceleration seismic hazard curve comparison [16]

The annual probability of failure, P_{Af}, in Eq. 7 can be extended over time intervals T for assessment of lifetime costs and benefits using Eq. 8:

$$P_{Tfj} = 1 - (1 - P_{Af})^T \qquad (8)$$

where P_{Tfj} is the T year probability of limit state exceedance. For this analysis 25 year, 50 year and 75 year time intervals are of interest, with the 75 year interval representing the design life for the expansion systems and the lower intervals offering insight into midlife benefit [32].

As shown by [33], the expected life cycle costs associated with seismic events can then be determined using Eq. 9.

$$E[LCC] = \frac{1}{\alpha t}(1 - e^{-\alpha t}) \sum_{j=1}^{4}\left(-C_j\left[ln\left(1 - P_{Tfj}\right) - ln\left(1 - P_{Tfj+1}\right)\right]\right) \qquad (9)$$

where, C_j is the repair cost associated with a damage state j, and α is a discount ratio used for converting future costs into present values.

The difference between the resulting bridge system or component life cycle costs determines the benefit of the upgrade as described in Eq. 10.

$$Benefit = E[LCC_{as-built}] - E[LCC_{Enhanced}] \qquad (10)$$

with the final ratio, $CBR = \frac{Benefit}{Investment\ Cost}$, quantifying the advantage of using the proposed enhancement. It should be noted that the resulting CBR is highly sensitive to the estimates assumed and therefore decision makers' assumptions may alter the resulting CBR.

Since expansion joints are not designed to transfer forces within the bridge system, highlighting the component cost benefit is insightful, versus a system wide assessment. This assessment seeks to separate secondary influences and concentrate on determining the benefit of the SMA enhancement over the standard expansion joint design, with 130 mm long equidistant devices.

When the component level cost benefit analysis is performed, the ratio of the magnitude of the indirect costs to the repair costs of the expansion joint itself is much greater. Therefore instead of applying a factor to the repair costs, indirect costs were calculated for rerouting based on costs set by the US Federal Highway Administration during a study on a rapid repair effort for a Virginia bridge crossing Broad Run. In this study an 11 mile rerouting distance was specified, along with an average per mile rerouting cost of $0.43/vehicle [34]. Average daily traffic for the I-24 Ohio River Bridge is approximately 28,100 based on data from the National Bridge Inventory for 2011 [35].

The seismic damage costs associated with damaged expansion joints mostly relates to the indirect socio-economic costs relating to rerouting as described above, rather than the material replacement and repair costs. Material costs relating to repair or replacement of elements in the expansion joint were assumed as the cost of the joint times repair ratios: slight = 0.03, moderate = 0.5, extensive = 0.9, complete = 1.0. The slight limit state relates to seal repairs to keep the joint watertight; the moderate and extensive limit states relate to repair and replacement of metal plates; and the complete limit state relates to failure of support bars necessitating replacement of the expansion joint. The total seismic damage costs therefore are the sum of the indirect costs related to traffic rerouting and the repair/replacement cost associated with the expansion joint.

The cost of the SMA enhanced modular bridge expansion joints used in the nonlinear time history analysis was based on 200$/spring and resulted in an investment cost of $18,000 over the base cost of an MBEJ, which was set at $147,218. This base cost was obtained from expansion joint costs presented in NCHRP 467 [36], i.e. $14 per meter of transverse length per mm of displacement capacity. Dexter [36] noted that for expansion joints that span multiple lanes and larger expansion gaps, the cost could approach one million dollars. Therefore accurately costing the manufacture and installation of these systems is key to predicting the benefit associated with SMA enhancement.

7. Results from Fragility Analysis

Table 2 lists the PSDM models for all the important bridge components monitored throughout the analysis for the three different bridge configurations analyzed.

This fragility analysis, quantifying the differences between three modular bridge expansion joint configurations, focuses on the longitudinal behavior of the bridge. It is observed through this fragility assessment that the abutments, expansion bearings and modular bridge expansion joints are seen to be those components mostly affected by longitudinal motion.

Table 2 Probabilistic seismic demand models for Sa – 1sec intensity measure

PSMDs – 130 mm MBEJ	ln(a)	b	R^2	σ
Abutment - Active	5.40	1.32	0.84	0.74
Abutment - Passive	4.61	1.25	0.80	0.80
Fixed Brg - Long	-1.341	0.16	0.43	0.24
Exp Brg - Long	4.22	1.08	0.83	0.63
MBEJ - Long	4.22	1.08	0.83	0.63
Column	-2.78	0.55	0.53	0.68
PSMDs – 171 mm MBEJ	ln(a)	b	R^2	σ
Abutment - Active	5.41	1.33	0.84	0.74
Abutment - Passive	4.60	1.24	0.80	0.80
Fixed Brg - Long	-0.95	0.75	0.82	0.46
Exp Brg - Long	4.31	1.31	0.86	0.68
MBEJ - Long	4.31	1.31	0.86	0.68
Column	-2.70	0.62	0.57	0.70
PSMDs – SMA MBEJ	ln(a)	b	R^2	σ
Abutment - Active	5.39	1.34	0.84	0.75
Abutment - Passive	4.59	1.25	0.80	0.80
Fixed Brg - Long	-1.00	0.76	0.82	0.46
Exp Brg - Long	4.29	1.34	0.86	0.69
MBEJ - Long	4.30	1.34	0.86	0.69
Column	-1.56	0.75	0.83	0.43

7.1 Component Fragility Curves

In Figure 7 three sets of fragility curves for the moderate, extensive and complete component level damage states are presented for comparison. These show the effectiveness of the SMA enhancement to improve the seismic response of the expansion joint as compared to the baseline and, particularly, the standard modular bridge expansion joint configurations. In this latter comparison it is seen from the fragility curve comparison that metal plate yielding (representative of the moderate limit state) commences in the standard configuration just past the maximum allowable service opening of 229 mm. This configuration represents the majority of installed modular bridge expansion joints and therefore the fragilities illustrate the vulnerability of currently installed systems to earthquake damage.

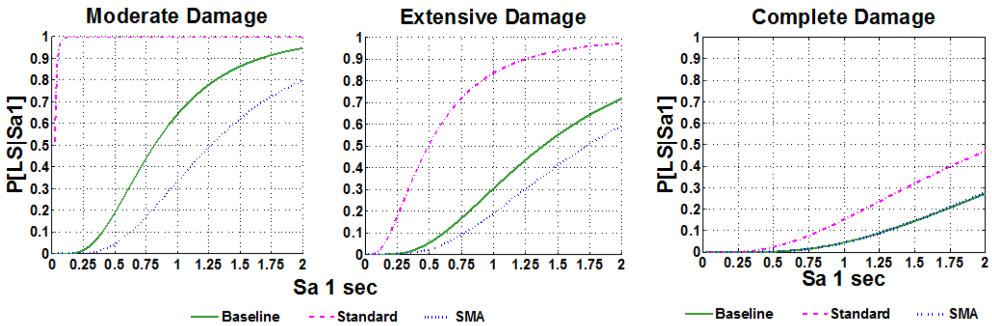


Figure 9 Fragility curves for the moderate, extensive and complete limit states for the three modular bridge expansion joints analyzed

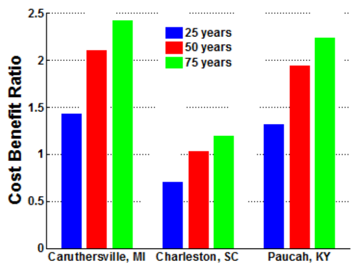
However, increasing the ability of the MEBJ to accommodate the seismic displacements through inclusion of the SMA spring greatly reduces the vulnerability of the modular bridge expansion joint considering uncertainty in the hazard characteristics, subsequent bridge system dynamic response, and capacity of the joints. The SMA spring accommodates detrimental seismic displacements while limiting joint failure; achievement of this target when subjected to a range of seismic ground motions is revealed through the fragility curves that show a reduction in fragility for different damage states when compared to the standard commonly installed modular bridge expansion joint. Recalling that the moderate damage state relates to yielding of the metal plates and the extensive damage state relates to complete failure of this component, the SMA spring reduces the forces transferred to this expansion joint element, adding additional seismic resistance to the system.

The fragility curves for the complete damage state for the baseline and SMA enhanced configurations are the same because this damage state relates to the support bar restraining elements yielding, which is a displacement capacity unrelated to the inclusion of the SMA spring. The standard MBEJ configuration uses shorter support bars resulting in a more fragile system, which is again unrelated to the equidistant system. The two damage states therefore, affected by the SMA enhancement are the moderate and extensive damage states. Based on accessibility to the damaged sections of the expansion joint, complete replacement or repair of the system are options for consideration within these limit states.

8. Results from Cost Benefit Analysis

Cost benefit analysis of the SMA enhancement versus the standard modular bridge expansion joint demonstrates the worthiness of the long-term investment opportunity for improving the seismic reliability of expansion joints. The results from a component level CBR analysis, assuming an 11-mile rerouting distance, are shown in Figure 8. The component fragilities are used to develop the component CBRs.

The cost benefit ratios take into consideration all the limit states for the modular bridge expansion joint. Here the cost benefit ratios for all three regions are greater than 1 signifying that the SMA spring economically improves upon the standard modular bridge expansion joint. The cost benefit ratios are assessed for three time frames, 25 years, 50 years and 75 years and for three seismic regions, Paducah Kentucky, Caruthersville Missouri and Charleston South Carolina.



75yr Lifetime	E-LCC	Benefit	Investment	CBR
Caruthersville				
130 mm Polymer MBEJ	$51,322	-	-	-
SMA Enhanced MBEJ	$7,625	$43,697	$18,000	2.43
Charleston				
130 mm Polymer MBEJ	$22,829	-	-	-
SMA Enhanced MBEJ	$1,339	$21,490	$18,000	1.19
Massac County				
130 mm Polymer MBEJ	$42,914	-	-	-
SMA Enhanced MBEJ	$2,644	$40,270	$18,000	2.24

Figure 10 Cost benefit ratio comparison for SMA enhanced MBEJ and the standard 130 mm long polymer configuration - 11 mile reroute (left) Graphical (right) Tabular

The ratios in Figure 8 show the increasing importance of the SMA enhancement as the time interval of interest increases. The structural components of the modular bridge expansion joints are ideally designed to have a 75 year life, therefore focus on this time interval is appropriate. For the three locations considered, the CBRs are greater than 1 for all the time intervals except in Charleston, South Carolina for the 25 year time interval. The seismic hazard in this region is lower than for the other two case studies, which leads to the lower observed benefit. However as the time interval increases the lifetime costs increase to a degree that the SMA enhancement benefits the reliability of the expansion system and indicates cost-effectiveness even for this lower hazard region. The expected life cycle costs (E-LCC) associated with seismic damage for the standard and SMA enhanced modular bridge expansion joint configurations for the 75 year time interval are shown in Figure 8.

The component level cost benefit ratios are sensitive to average daily traffic estimates and assumed costs associated with rerouting distance and repair cost ratios. Increasing the rerouting distance to 48 km significantly increases the cost benefit ratios, by as much as an additional 93%. Changing the repair cost ratio for the extensive damage state from 0.9 to 0.5 alters the CBR for the Paducah, KY 75 year time interval from 2.24 to 2.19. This 2% change shows how the indirect costs dominate the costs related to damage of the expansion system, an aspect that the SMA enhancement targets through damage prevention.

9. Conclusion

By minimally increasing the cost of a service level MBEJ through enhancement with SMAs, the seismic performance of this joint type can be significantly improved, thus reducing life cycle costs and limiting damage associated with failed components. Seen through the component cost benefit analysis, loss of functionality affects the costs associated with seismic damage, especially when potential road closures and rerouting affect traffic for up to 7 days. These socio-economic factors dominate the loss costs of damaged expansion joints. An SMA enhanced joint reduces these life cycle costs by improving seismic performance. Based on the results, for an investment that is roughly 14% of the total expansion joint cost, significant benefits can be obtained that improve functionality post seismic event.

The fragility and cost benefit analyses presented in this paper are the first to account for modular bridge expansion joint contributions in a bridge's seismic analysis. Fragility curves have not before been generated for expansion joints, and the inclusion of expansion joint behavior in the nonlinear time history analysis of a bridge model is a unique contribution to a bridge community that wants to better understand components that influence post-event functionality.

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