RETROFITTING TRANSPORTATION SYSTEMS TO ENSURE RESILIENCY

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ABSTRACT :

This paper presents a seismic risk assessment of the transportation network in Charleston, SC, to support the development of mitigation strategies and emergency planning and preparedness efforts. In particular, this study focuses on the impact of retrofit on reducing the expected damage and improving the resiliency of the network. This study includes an inventory analysis of the roughly 375 bridges in the Charleston area, and convolution of the seismic hazard with fragility curves analytically derived for classes of bridges common to this part of the country, and replacement cost estimates using relevant region-specific data. Using state-of-the-art tools, the distribution of potential bridge damage and functionality is evaluated for several scenario events and several retrofit strategies. The results show that retrofitting bridges based on retrofitted bridge fragility curves can be an effective way to reduce the economic losses and improve the resiliency of the system.

KEYWORDS: Seismic risk assessment, fragility curves, retrofit, bridges, functionality

1. INTRODUCTION

The highway system is a critical infrastructure component whose performance can have far-reaching impacts on an affected community or region. For example, a functioning highway system is important for emergency response efforts, and having access to victims and critical facilities, such as hospitals. Evidence from past earthquake events has also revealed the economic consequences of highway system failure. Considerable direct losses associated with the damage include such items as repair and replacement of bridges. Indirect economic consequences can far outweigh these direct costs, including such items as travel time delay or business disruption. Due to the interconnectedness of the highway system with a number of infrastructure systems and activities in a region, the total impact of highway damage may be difficult to capture. However, it is evident that having a healthy understanding of the vulnerability of the transportation infrastructure and the seismic risk to the highway system can support risk mitigation and retrofit selection to reduce the economic and social consequences of a future earthquake event.

Assessing and effectively retrofitting the transportation system is a particular challenge in regions such as the Central and Southeastern United States. This region tends to have large but infrequent events, and a large population of bridges that were designed with little or no seismic consideration. Funds are typically limited for retrofit, and current approaches are not ideal for identifying optimal measures where many bridge types and many options for retrofit exists. This paper focuses on an approach to retrofit assessment, with the goal of maximizing functionality following an earthquake event and reducing anticipated economic losses. Using a seismic risk assessment framework, recently developed suites of fragility curves for existing and retrofitted bridges, and damage-functionality relationships, a regional assessment is performed for Charleston, South Carolina to aid in resiliency enhancement. In general, resilient systems have a lower likelihood of failure and anticipated associated consequences, such as downtime and associated economic losses. Often, the resilience of a system is measured by the level of post event functionality and restoration over time. The Charleston transportation system will be evaluated under a range of retrofit strategies for enhancement of these metrics of resilience.

2. RISK ASSESSMENT METHODOLOGY

Methodologies for seismic risk assessment of highway systems have been presented by several researchers in the field of lifeline earthquake engineering (Werner et al, 1997; Chang et al, 2000). These methodologies offer a potential framework for assessing likely bridge damage, direct losses due to repair and replacement of structures, and some extend this evaluation to include an assessment of the impact of the event on network performance and the resulting indirect economic losses. Werner and Taylor (2002) highlighted the importance of observing component functionality in addition to addressing the damage state. Knowing whether a bridge will be fully closed (0% functional), partially open (50% functional), or fully open (100% functional) provides a means of analyzing networks as a whole.

A general framework for the risk assessment method applied in this study is shown in Figure 1. While probabilistic analyses are also of interest, this paper presents the results of scenario earthquake events with a range of different magnitudes occurring outside of Charleston in Summerville, SC. This is the site a magnitude 7.3 event that struck on August 31, 1886, recognized as the most damaging earthquake in the Southeast United States (USGS, 2007).

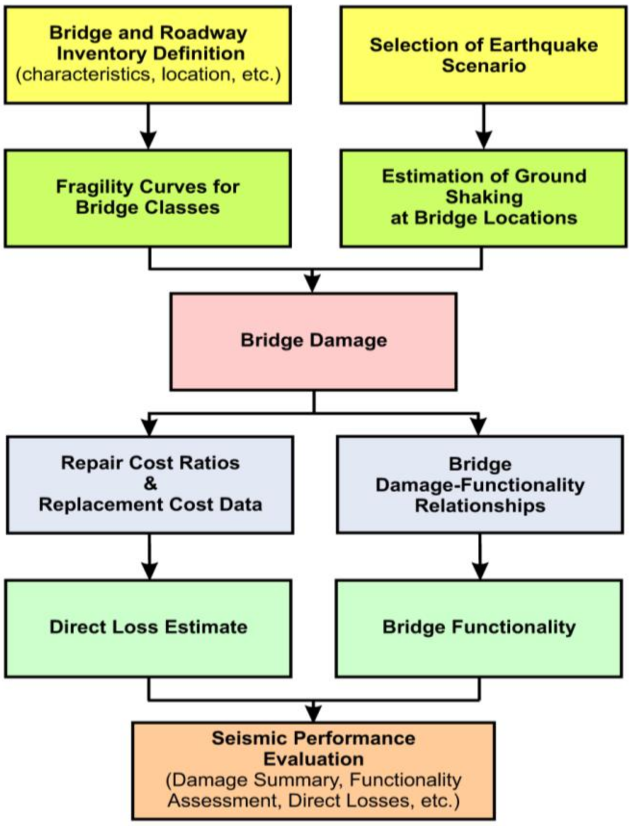

Figure 1 Schematic of general seismic risk assessment methodology applied

3. BRIDGE FRAGILITY, FUNCTIONALITY, AND LOSS ESTIMATION

3.1. As-built and Retrofitted Bridge Fragility Curves

The region of interest for the Charleston, SC study includes approximately 375 bridges ranging in material and construction type. The general classes of bridges in the inventory include common classes found in the Central and Southeastern United States, for which representative fragility curves have been developed. These fragility curves depict the probability for meeting or exceeding different levels of damage (slight, moderate, extensive, or complete) conditioned upon the ground motion intensity, and are used to evaluate the expected damage state for the bridge. These damage estimates are an indication of the *"robustness"* of the infrastructure, which is a measure of resilience used by some researchers referring to the system's ability to withstand the event without significant degradation (Tierney and Bruneau, 2007).

The nine classes for which fragility curves have been developed by Nielson and DesRoches (2007) include the following: single span steel girder, single span concrete girder, multi-span simply supported (MSSS) steel girder, MSSS concrete girder, multi-span continuous (MSC) steel girder, MSC concrete girder, MSSS concrete box, MSC slab, and MSSS slab bridges. Common retrofit measures that may potentially help to overcome the vulnerabilities of these bridges have been evaluated for their impact on bridge fragility (Padgett, 2007). The retrofits considered are restrainer cables (RC), shear keys (SK), steel jackets, seat extenders (SE), elastomeric isolation bearings, steel jackets (Figure 2) and common combinations of these measures. Details on the methodology for the fragility curve development can be found elsewhere (Padgett, 2007). The bridge system fragility curves are derived for each bridge type and retrofit measure estimated as lognormal distributions of the form

$$P[DS \mid PGA] = \Phi\left(\frac{\ln(PGA) - \ln(med_{sys})}{\zeta_{sys}}\right) \quad (1)$$

where med_{sys} is the median value of the system fragility (in units of *g* PGA), and ζ_{sys} is the dispersion, or logarithmic standard deviation, of the system fragility. A sample comparison of the as-built and retrofitted fragility curves for the multi-span continuous steel girder bridges are shown in Table 1 and plotted for two damage states in Figure 3.

(a) (b) (c) (d) (e)

Figure 2 Bridge retrofits considered: (a) steel jackets, (b) elastomeric isolation bearings, (c) restrainer cables, (d) seat extenders and (e) shear keys

Table 1. Lognormal parameters for the fragility of the MSC Steel bridge class with a range of retrofit measures.

Condition	Slight		Moderate		Extensive		Complete	
	med_{sys}	ζ_{sys}	med_{sys}	ζ_{sys}	med_{sys}	ζ_{sys}	med_{sys}	ζ_{sys}
As-Built (Pre-Retrofit)	0.19	0.56	0.36	0.54	0.44	0.56	0.57	0.59
Steel Jackets	0.20	0.57	0.40	0.56	0.50	0.58	0.67	0.62
Elastomeric Isolation Bearings	0.26	0.72	0.43	0.70	0.56	0.71	0.92	0.73
Restrainer Cables	0.20	0.57	0.37	0.55	0.49	0.57	0.67	0.60
Seat Extenders	0.19	0.56	0.36	0.54	0.44	0.56	0.69	0.58
Shear Keys	0.21	0.56	0.41	0.56	0.50	0.59	0.62	0.62
Restrainer Cables & Shear Keys	0.21	0.57	0.41	0.57	0.53	0.59	0.69	0.61
Seat Extenders & Shear Keys	0.21	0.56	0.41	0.56	0.51	0.59	0.80	0.61

3.2. Bridge Functionality Relationships and Loss Estimates

One of the critical input needs for SRA is the relationship between extent of damage to a bridge and the resulting loss-of-functionality of the network component. The functionality is often a result of closure decisions made by post-earthquake inspectors, as well as the procedures for repair of the bridge. Recent work has addressed the need for development of relationships between bridge damage and functionality (allowable traffic carrying capacity) by use of a web-based survey which elicits expert opinion data on repair procedures and restoration of bridge functionality. The anticipated traffic carrying capacity over time due to inspection and closure decisions as well as repair is shown in Figure 4. Data from the survey was used to refine the limit states for the fragility analysis and ensure that each damage state can be associated with a given level of functionality. Further details of the development of these relationships and limit state refinement may be found in (Padgett, 2007 and Padgett and DesRoches, 2007). The resulting functionality and restoration of service is a direct indication of the system's resilience, often associated with the term *"rapidity"* (Tierney and Bruneau, 2007).

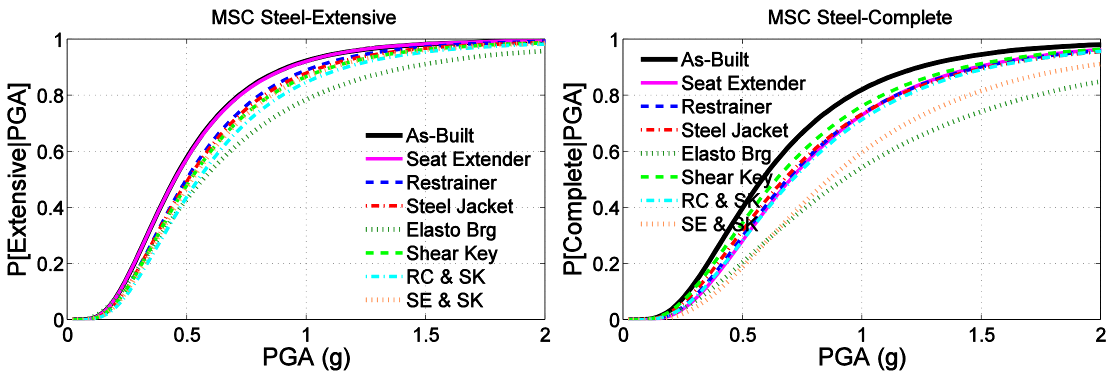

Figure 3 Comparison of the fragility of the MSC steel bridge with various retrofit measures at two damage states

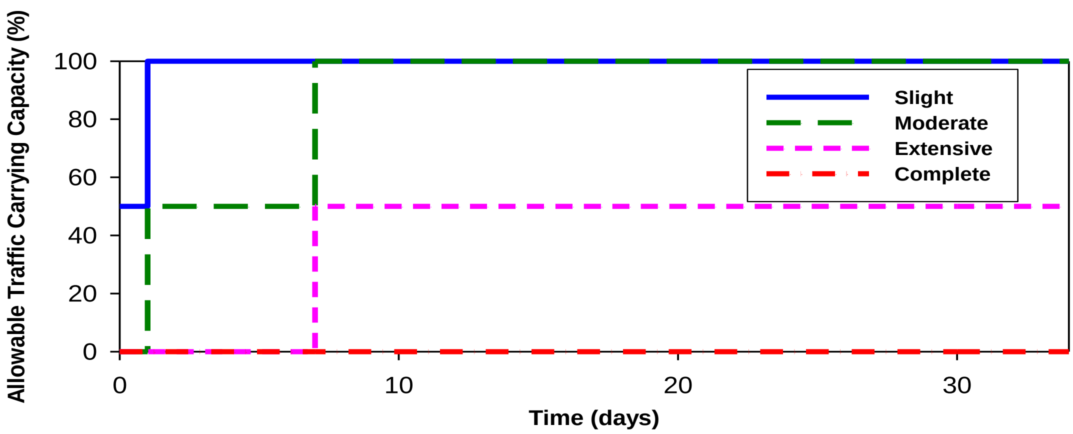

Figure 4 Bridge functionality associated with each damage state

Direct losses associated with repair and replacement are estimated for the Charleston risk assessment. The repair costs associated with each damage state are assumed to be a percentage of the replacement cost of the bridge utilizing Basoz and Mander's (1999) estimates of the best mean repair cost ratio. Region specific data on bridge construction and replacement costs were provided by the state department of transportation (SCDOT). Indirect losses associated with increased travel time in the system and extended downtime are not evaluated as a part of this paper. Avoiding economic losses is often a key objective of owners seeking to retrofit or upgrade the transportation system, though minimum initial investment is critical when limited funds are available for seismic retrofit.

4. RESULTS

4.1. As-built Response

Seismic risk assessment was performed for the three deterministic hazards M_w 4.0, 5.5, and 7.0 with an epicenter in Summerville, SC, which is located just northwest of downtown Charleston The distribution of damage for the M_w 5.5 and 7.0 hazard levels are shown in Figure 5. The numbers (+) shown to the right of the bars indicate the increase in the number of bridges as compared to the lower magnitude. For the M_w 5.5 event, approximately 182 of the bridges are in the moderate or higher damage state, representing an increase of 148 bridges when compared to the M_w 4.0 event. The M_w 7.0 event shows that over 272 bridges are in the moderate or higher, which represents 85% of all of the bridges in the study area. When compared with the M_w 5.5 event, this represents an additional 90 bridges in the moderate or higher damage states. Moreover, the M_w 7.0 event results in a significant increase in the number of bridges in the extensive and complete damage state, when compared with the M_w 5.5 event. Eleven bridges had complete damage or higher in the M_w 5.5 event, while over 45 bridges had complete damage or higher in the M_w 7.0 event.

It is interesting to note that a magnitude 4.0 scenario results in only slight or moderate damage to 65 bridges, with the remaining bridges having no damage. This is an indication that the M_w 4.0 earthquake might be the threshold at which inspection teams are mobilized following an earthquake event.

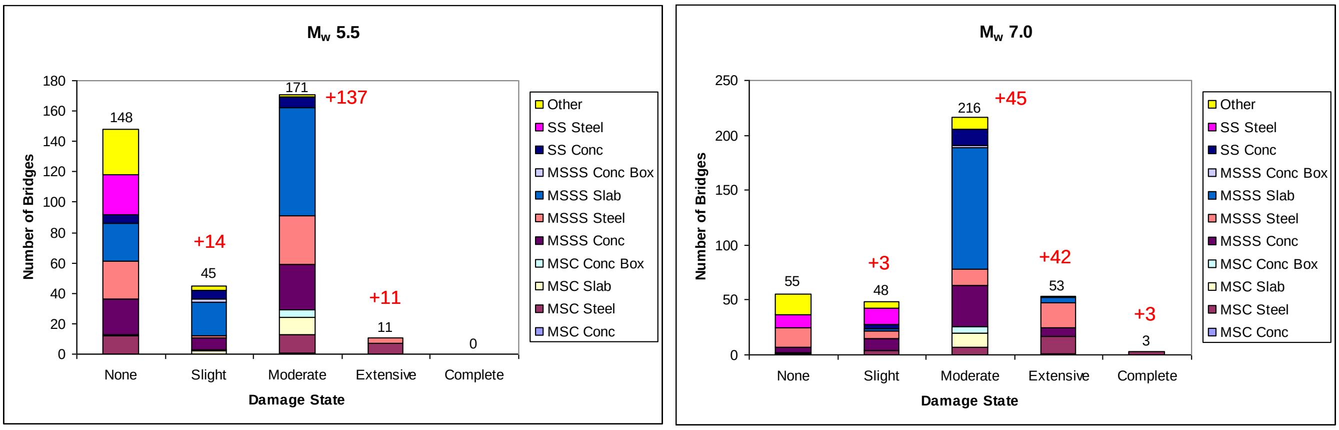

Figure 5 Damage state distribution by bridge type and damage state for M_w 5.5 and 7.0 events.

4.2. Response for Retrofitted System

The seismic risk assessment was repeated to assess the impact of various retrofit measures on the distribution of damage for a M_w 7.3 earthquake event. All of the retrofit measures discussed in section 3.1 were evaluated. Figure 5 shows the results for the cases with elastomeric bearings and restrainer cables. For the cases with elastomeric bearings and restrainer cables, all 375 bridges were retrofitted, independent of the bridge type or damage state. The third retrofit case which was evaluated is the case where the retrofit measure was specifically chosen for the bridge based on the most effective retrofit measure for that particular bridge and damage state. This was based on the fragility values noted in Table 1. Furthermore, instead of retrofitting all bridges, only the bridges that were in either the complete or extensive damage state were retrofitted, resulting in a significant reduction in the number of bridges requiring retrofit (77 bridges).

As shown in Figure 6, for the pre-retrofit case, 77 bridges are in the extensive or complete damage state. Retrofitting the bridges with restrainer cables, results in 62 bridges being in the extensive or complete damage state. This indicates that for the bridge inventory as a whole, restrainer cables are not very effective in reducing their vulnerability. For the case where all of the bridges are retrofitted with elastomeric bearings, 40 bridges remain in the complete or extensive damage state. It is clear that elastomeric bearings are more effective in reducing the bridge vulnerability as compared to the restrainer cables. Finally, the case with selection of retrofit measures based on the median value fragility improvement results in 31 bridges being in the extensive or complete damage states. Selecting choosing retrofit measures based on the fragility curves results in the overall best performance of the bridges in the Charleston area when compared with restrainer cables or elastomeric bearings.

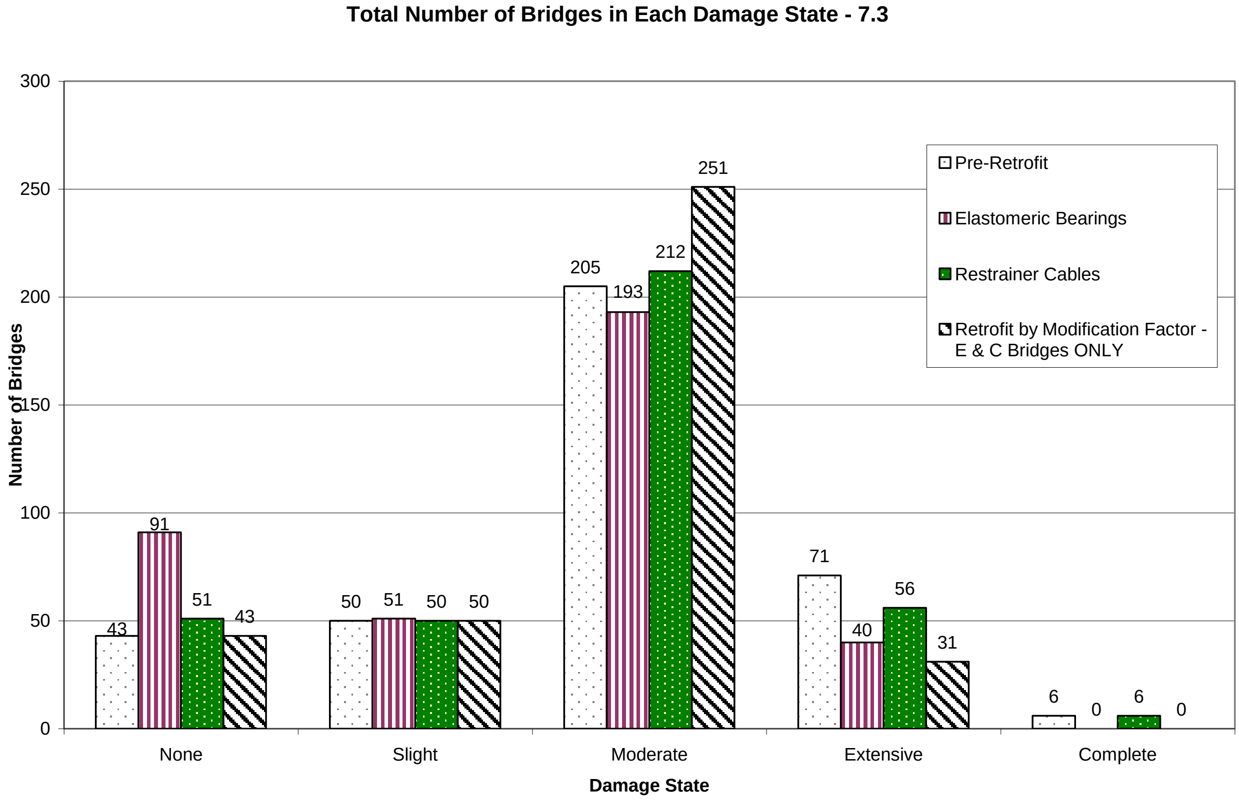

Figure 6 Distribution of bridges by damage state and retrofit approach for a Mw 7.3 event.

4.3. Functionality of Retrofitted System

An assessment of the distribution of bridge damage is important in a seismic risk assessment. However, the critical information required for determining indirect losses and evaluating the resiliency in the system is the functionality of the system over time. Figure 7 shows the expected functionality of the entire network, based on the weighted bridge functionality (WBF), as a function of the various retrofit measures. The weighted bridge functionality is determined by taking a weighted average of the functionality of each bridge, *n*, in the network as shown in the following equation:

$$WBF = \frac{1}{N}\sum_{n}^{N} Functionality_n$$

This provides a composite measure of the functionality of all of the bridges in the transportation network and reveals the anticipated restoration over time.

Recall, for the elastomeric bearing and restrainer retrofits, the entire inventory (375 bridges) are retrofitted, independent of the damage state. However, for the case when retrofit measures are selected based on the most effective retrofit for that damage state and bridge type, only bridges in the extensive and complete damage state are considered. For the pre-retrofit case, the functionality immediately following the event is approximately 18%, increases to 52% after 1 day, and further increases to 88% at 7 days. The results with elastomeric bearings increase the functionality to 32% immediately following the event, 64% after 1 day, and 94% at day 7. The significant increase in functionality during the early phases following the earthquake for the elastomeric bearing retrofit is a result of the fact that bridges that were in the slight or moderate damage state would be significantly improved by the elastomeric bearing retrofit. In contrast, the results with retrofit by modification factor leads to primarily benefits in functionality after 7 days. This is because the retrofit by modification factor only addresses the extensive and complete damage states, which tend to impact the functionality most for the period beyond 7 days. It is clear from these results that if short term (1-7 days) functionality is a primary concern, bridges with any level of damage should be considered for retrofit.

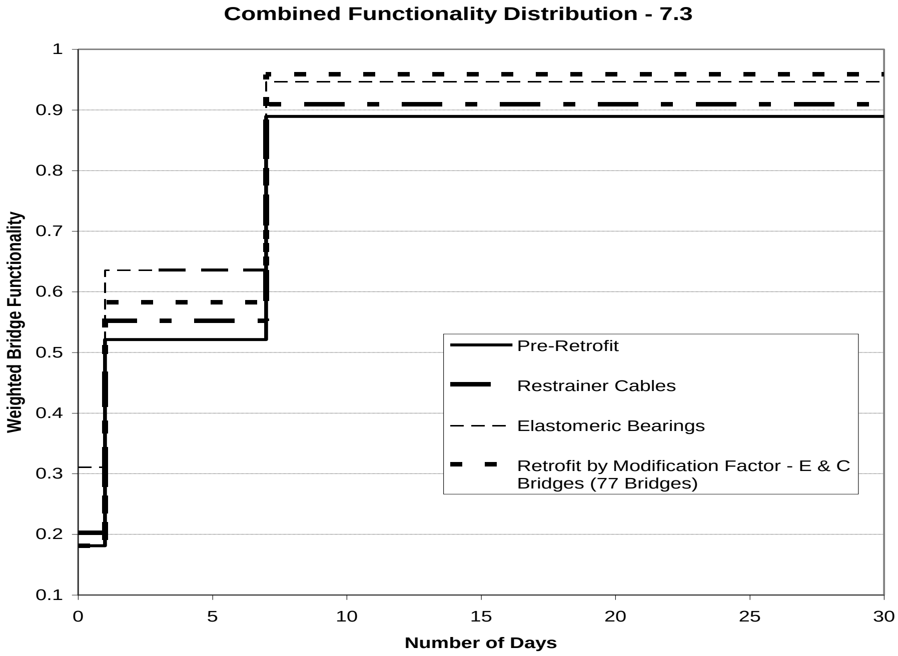

Figure 7 System functionality at 0, 1, 7, and 30 days for pre-retrofit and various retrofit measures for M_w 7.3 event.

4.4. Economic Losses

The calculation of expected economic losses is based on the damage state and the repair and construction data from the state of South Carolina. Table 2 shows a comparison of the direct economic losses for the pre-retrofit, retrofit of all bridges with restrainer cables (375 bridges), and retrofit based on the modification factor (77 bridges). The analysis is performed for both magnitude 5.3 and 7.3 events.

For a M_w 5.3 seismic event, direct economic losses are estimated to be approximately $51 million dollars. Restrainer cables reduce the direct losses by 12%, while the retrofit based on modification factor reduces the direct losses by 40%. Similar reductions are for the M_w 7.3 event. The restrainer cables and retrofit based on modification result in 10%, and 25% reduction in direct losses, respectively. Despite retrofitting significantly fewer bridges, the selection of retrofit based on modification factor results in a much more effective means to retrofit bridges. Further reductions in losses can be obtained by retrofitted bridges that are also in the slight and moderate damage states. However, given the limited funding for retrofit in many states, this might not be a realistic approach.

Table 2. Estimated Direct Economic Losses for 2 Earthquake Magnitudes and Various Retrofit Measures

	Pre-Retrofit	**Restrainer Cables**	**Based on Modification Factor**
Magnitude 5.3	$50,850,000	$43,940,000	$30,570,000

Magnitude 7.3	$105,000,000	$93,770,000	$77,970,000

5. SUMMARY

A seismic risk assessment is performed for Charleston, SC to assess the impact of retrofit on the reduction of damage and improvement of resiliency in the transportation network in Charleston, SC. Recently developed critical input tools for the seismic risk assessment are applied in the framework, including as-built and retrofitted bridge fragility curves, functionality relationships, and region specific replacement cost data. The resiliency is evaluated based on likely bridge damage which indicates the robustness, direct economic consequences, and improvement in post event functionality and anticipated restoration indicating the rapidity. The results show that as the magnitude of the earthquake increases from a Mw 5.5 to a 7.0, a significant increase in the number of bridges in the complete or extensive damage state is observed. The impact of retrofit is assessed by comparing the distribution of damage, functionality, and economic losses as a function of three different retrofit approaches. One of the most retrofit approaches considered includes retrofitting the bridges expected to suffer higher levels of damage with the most effective measure identified based on improvement in the fragility curve. The results show that retrofitting bridges based on the fragility curves is the most effective way to reduce the economic losses, and improve the long-term functionality of the network. The results show that retrofitting 25% of the bridges with this approach results in better performance than retrofitted all bridges using restrainer cables. This indicates that for regions where limited funds may be available for seismic retrofit, improved resiliency can still be achieved through wise selection of bridges and retrofit measures which may be supported by the seismic risk assessment framework and input tools.

REFERENCES

Basoz, N., and Mander, J. (1999). "Enhancement of the Highway Transportation Module in HAZUS", in *Report to National Institute of Building Sciences*. Washington, D.C.

Chang, S. E., Shinozuka, M., Moore, J. E. (2000) "Probabilistic earthquake scenarios: Extending risk analysis methodologies to spatially distributed systems," *Earthquake Spectra*, **16(3)**, 557-572.

Eguchi, R. T., Goltz, J. D., Taylor, C. E., Chang, S. E., Flores, P. J., Johnson, L. A., Seligson, H. A., and Blais, N. C. (1998). "Direct economic losses in the Northridge Earthquake: A three-year post-event perspective." *Earthquake Spectra*, **14(2)**, 245-264.

Nielson, B. and DesRoches, R (2007). "Analytical Fragility Curves for Typical Highway Bridge Classes in the Central and Southeastern United States." *Earthquake Spectra*, **23(3),** 615-633.

Padgett, J. (2007) "Vulnerability Assessment of Retrofitted Bridges Using Probabilistic Methods," PhD thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta.

Padgett, J. E., DesRoches, R. (2007) "Bridge Functionality Relationships for Improved Seismic Risk Assessment of Transportation Networks," *Earthquake Spectra*, **23(1),** 115-130.

Tierney, K. and Bruneau, M. (2007). "Conceptualizing and Measuring Resilience: A key to disaster loss reduction." *TR News*, May-June 2007, 14-18.

USGS, "Earthquake Hazards Program Website." http://earthquake.usgs.gov/, Date Accessed: January 11, 2007.

Werner, S. D., Taylor, C. E., and Moore, J. E. (1997) "Loss estimation due to seismic risks to highway systems," *Earthquake Spectra*, **13(4),** 585-604.

Werner, S. D. and Taylor, C. E. (2002). "Component Vulnerability Modeling Issues for Analysis of Seismic Risks to Transportation Lifeline Systems." *Acceptable Risk Processes– Lifelines and Natural Hazards*, Council on Disaster Reduction and Technical Council for Lifeline Earthquake Engineering.