

Development of fragility curves for retrofitted multi-column bridge bent subjected to near fault ground motion



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SUMMARY:

This study focuses on developing fragility-based seismic vulnerability assessment techniques for seismically retrofitted multi-column bridge bent. Fragility curves are developed using Probabilistic Seismic Demand Model (PSDM) to assess the relative performance of different retrofit methods under near fault ground motions. Two different retrofit techniques namely CFRP jacketing and ECC jacketing are used in this study. The distinctive and catastrophic features of near fault ground motions place serious demand on structures located in the near field region of an earthquake and require special attention. In order to investigate the near fault ground motions effects, a total of 20 near fault ground motions are utilized to evaluate the likelihood of exceeding the seismic capacity of the retrofitted bridge bent. Results obtained from this study indicate that the properties of retrofitting materials have a significant effect on the damage probability of the retrofitted bridge bents. The findings can serve as a guide to express the impact of retrofit on the bridge bent vulnerability.

Keywords: Bridge bent, Seismic retrofit, Fragility, Near-fault, Damage.

1. INTRODUCTION

Highway bridges are crucial components in a transportation network. The devastating nature of recent earthquakes and their socio-economic impact have increased the awareness of assessing the potential seismic risk and vulnerability of highway bridge infrastructures. Many existing bridges in North America which were built prior to the enforcement of modern seismic design guidelines (ATC-2003, CSA-2010) are inherently vulnerable as different modes of failure have been observed under the action of moderate or strong earthquakes. Many of them were designed without any earthquake resistance criterion; others were designed to resist horizontal actions but without the principles of the capacity design or are built at a site in an area where the seismic hazard has been re-evaluated and increased (ATC-2003, CSA-2010). In order to upgrade the seismic performance of existing vulnerable RC structures, various rehabilitation techniques are available. Some major techniques for structural rehabilitation of RC bridges include encasing columns and beam column joints using either steel jacket, reinforced concrete (RC) jacket, carbon fiber reinforced polymer (CFRP) wrap or engineered cementitious composites (ECC) jackets.

Vulnerability assessment of bridges is widely recognized to be useful for prioritization of seismic retrofitting decisions, disaster response planning, estimation of direct monetary loss, and evaluation of loss of functionality of highway systems in the event of an earthquake. The seismic vulnerability of highway bridges is usually expressed in the form of fragility curves, which display the conditional probability where the structural demand (structural response) caused by various levels of ground shaking exceeds the structural capacity defined by a damage state.

Major earthquakes in recent years have demonstrated that near fault ground motions are the most severe earthquake type loading that the structures experience. Near fault ground motions possess some unique characteristics such as high PGA/PGV ratio and wide range of accelerations in their response spectra (Somerville, 2002). They produce damaging and impulsive effects on structures, which require

some special attentions. The objective of this study is to assess the fragility of a non-seismically designed multi column bridge bent retrofitted with two different rehabilitation techniques, namely CFRP jacketing and ECC jacketing which to date has not been adequately addressed for near fault ground motions.

2. FRAGILITY FUNCTION METHODOLOGY

Fragility curve allows the evaluation of potential seismic risk assessment of any structure. Fragility function describes the conditional probability i.e. the likelihood of a structure being damaged beyond a specific damage level for a given ground motion intensity measure. The fragility or conditional probability can be expressed as

$$\text{Fragility} = P[LS|IM=y] \quad (2.1)$$

where, *LS* is the limit state or damage state of the structure or structural component, *IM* is the ground motion intensity measure and *y* is the realized condition of the ground motion intensity measure.

In order to develop fragility curves different methods and approaches have been developed. Depending on the available data and resources, fragility functions can be generated empirically based on post-earthquake surveys and observed damage data from past earthquakes (Basoz et al. 1999; Yamazaki et al. 2000). However, limited damage data and subjectivity in defining damage states limit the application of empirical fragility curves (Padgett and DesRoches, 2008). In absence of adequate damage data, fragility functions can be developed using a variety of analytical methods such as elastic spectral analyses (Hwang et al. 2000), nonlinear static analyses (Shinozuka et al. 2000) and nonlinear time-history analyses (Hwang et al. 2001; Choi et al. 2004). In order to generate analytical fragility curves, structural demand and capacity needs to be modeled. In this study probabilistic seismic demand model (*PSDM*) was used to derive the analytical fragility curves using nonlinear time-history analyses of the retrofitted bridge bents. Although this is the most rigorous method, yet this is the most reliable analytical method (Shinozuka et al. 2000). The *PSDM* establishes a correlation between the engineering demand parameters (*EDP*) and the ground intensity measures (*IM*). In the current study, displacement ductility demand of retrofitted bridge bent was considered as the *EDP*, and the peak ground acceleration (*PGA*) was utilized as intensity measure (*IM*) of each ground motion record.

Two approaches are used to develop the *PSDM*: the scaling approach (Zhang and Huo 2009) and the cloud approach (Choi et al. 2004; Mackie and Stojadinovic 2004). In the scaling approach, all the ground motions are scaled to selective intensity levels and an incremental dynamic analysis (*IDA*) is conducted at each level of intensity; however, in the cloud approach, un-scaled earthquake ground motions are used in the nonlinear time-history analysis and then a probabilistic seismic demand model is developed based on the nonlinear time history analyses results. In the current study, the cloud method was utilized in evaluating the seismic fragility functions of the retrofitted bridge bents. In the cloud approach, a regression analysis is carried out to obtain the mean and standard deviation for each limit state by assuming the power law function (Cornell et al. 2002), which gives a logarithmic correlation between median *EDP* and selected *IM*:

$$EDP = a (IM)^b \text{ or, } \ln (EDP) = \ln (a) + b \ln (IM) \quad (2.2)$$

where, *a* and *b* are unknown coefficients which can be estimated from a regression analysis of the response data collected from the nonlinear time history analyses.

In this study Incremental Dynamic Analysis (*IDA*) has been carried out to create sufficient data for the probabilistic seismic demand model. In the *IDA* each increment involves a full nonlinear time history analysis of the structure to capture its behavior under that particular ground motion intensity. *IDA* was carried out by scaling each ground motion to ten intervals and generating 200 data sets for use in the regression analysis of demand for a given *IM*. In order to carry out the *IDA*, the ground motions are

not scaled to a particular intensity rather they are scaled from a very low *PGA* to the maximum *PGA* of the respective ground motion. This helped in reducing the computational time and producing adequate damage data for generating fragility curves. Each intensity level of a particular ground motion can be considered as one time history analysis. Thus it was possible to generate sufficient damage data corresponding to different intensity levels. The dispersion of the demand, $\beta_{EDP|IM}$, conditioned upon the *IM* can be estimated from Equation 2.3 (Baker and Cornell 2006).

$$\beta_{EDP|IM} = \sqrt{\frac{\sum_{i=1}^N (\ln(EDP_i) - \ln(aIM^b))^2}{N-2}} \quad (2.3)$$

where, N = number of total simulation cases.

With the probabilistic seismic demand models and the limit states corresponding to various damage states, it is now possible to generate the fragilities (the conditional probability of reaching a certain damage state for a given *IM*) using Equation 2.4 (Nielson 2005).

$$P[LS|IM] = \phi\left[\frac{\ln(IM) - \ln(IM_n)}{\beta_{comp}}\right] \quad (2.4)$$

$$\text{where, } \ln(IM_n) = \frac{\ln(S_c) - \ln(a)}{b} \quad (2.5)$$

$\ln(IM_n)$ is defined as the median value of the intensity measure for the chosen damage state (slight, moderate, extensive, and collapse), a and b are the regression coefficients of the *PSDMs* and the dispersion component is presented in Equation 2.6 (Nielson 2005).

$$\beta_{comp} = \frac{\sqrt{\beta_{EDP|IM} + \beta_c^2}}{b} \quad (2.6)$$

where, S_c is the median and β_c is the dispersion value for the damage states of the bridge pier.

3. BRIDGE BENT DETAILS

The northbound lanes of the South Temple Bridge is considered in this study (Pantelides and Gergely, 2002) for evaluating the seismic fragility of the retrofitted multi-column bridge bent. The bridge was considered seismically deficient as it had inadequacy in the amount of reinforcement and seismic detailing. This bridge bent was retrofitted by Pantelides and Gergely (2002) using CFRP jacketing. They developed design equations for CFRP jacketing and performed both experimental study and analytical verification of their results. The bent consists of three columns and a bent cap, as shown in Figure 1. A concrete deck of 21.87 m span was supported by two bents and each bent supported eight steel girders. A gravity load of 240 kN was carried by each steel girder. Reinforcement details of the column, bent cap, and joints are also shown in Figure 1. The bent column had inadequate transverse reinforcement in the lap-splice region. Transverse hoops in the bent cap joints were absent, and columns had insufficient tie spacing in the plastic hinge regions, which is the most vulnerable portion of a column. The reinforcing steel in the bridge bent had yield strength of 275 MPa, while the compressive strength of the concrete was 21MPa.

3.1. Details of Retrofitting Techniques

In order to design the two different retrofitting techniques, a response spectrum analysis was carried out to determine the design base shear. As the bridge bent is located in Salt Lake City, Utah, USA, the design response spectrum for this location was obtained (Swensen and Wong, 2011). Determining the

time period and modal mass participation factors from eigenvalue analysis, the design base shear for each retrofitted bridge bent was calculated using the square root sum of square (SRSS) method.

In this study the CFRP composite jacket retrofitting technique was implemented from Pantelides and Gergely (2002), which has a tensile strength of 628 MPa, initial stiffness of 6.5×10^4 MPa and ultimate axial strain of 10mm/m. The material is a carbon fiber/epoxy resin composite with 48,000 fibers per tow unidirectional carbon fibers. The number of tows per 25.4 mm of sheet (pitch) was 6.5, and the width of the carbon fiber sheets was 457 mm. The thickness of the CFRP jacketing was calculated to be 3.42 mm.

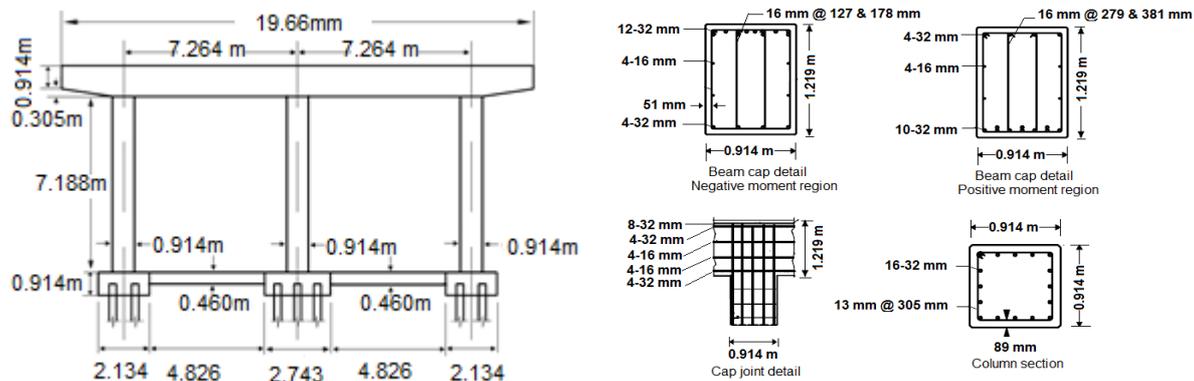


Figure 1. South Temple Bridge bent dimensions and reinforcement details (adapted from Pantelides and Gergely, 2002)

Due to its superior property over regular concrete, ECC jacketing was utilized as another retrofitting technique in this study. Because of the strain-hardening property of ECC, this ductile material behaves more like steel than traditional concrete. The jacket thickness calculated was 80 mm. For retrofitting with ECC jacket, no additional reinforcement was provided. The ECC used in this study has a compressive strength of 80 MPa and a tensile strength of 6.5 MPa.

4. FINITE ELEMENT MODELING

The analytical model of the bridge bent is approximated as a continuous 2-D finite element frame using the SeismoStruct nonlinear analysis program (SeismoStruct, 2010). Nonlinear static pushover and incremental dynamic time-history analyses have been performed to determine the performances of the retrofitted bridge bents. 3-D inelastic beam elements have been used for modeling the beams and the columns. Here, fiber modeling approach has been employed to represent the distribution of material nonlinearity along the length and cross-sectional area of the member. The confinement effect of the concrete section is considered on the basis of reinforcement detailing. To develop the analytical model Menegotto-Pinto steel model (Menegotto and Pinto, 1973) with Filippou (Filippou et al., 1983) isotropic strain hardening property is used for reinforcing steel material. The yield strength, strain hardening parameter and modulus of elasticity of steel are considered as 275MPa, 0.5% and 2×10^5 MPa, respectively. Nonlinear variable confinement model of Madas and Elnashai (1992) with compressive strength of 21MPa and tensile strength of 1.7MPa has been used for concrete. CFRP confined concrete model developed by Ferracuti and Savoia (2005) has been implemented. In this model the confinement effect of the FRP wrapping follows the rules proposed by Spoelstra and Monti (1999).

The CFRP retrofitted bridge bent has been modeled in SeismoStruct (2010) with jacketed section. To develop the analytical model for bridge bent retrofitted with ECC jacket, another finite element software ZeusNL (2011) was employed. Similar concrete and steel model was used for modeling bridge bent where ECC jacket was modeled following the constitutive relationship developed by Han et al. (2003). Although this study used two different finite element software, both the software uses same modeling approach i.e. fiber modeling approach. Moreover, both software has similar

constitutive models for concrete and steel and uses similar algorithm for static and dynamic analysis and these allowed producing comparable results.

5. SELECTION OF GROUND MOTIONS

A suite of 20 near fault ground motions are used in this study to develop fragility curves for the retrofitted bridge bents. The near fault ground motions were obtained from SAC Joint Venture Steel Project Phase 2 (SAC 2000). The characteristics of the earthquake ground motion records are presented in Table 5.1. All these ground motions have very high *PGA* ranging from 0.45g to 1.07g with epicentral distances less than 10 km. Figure 2a shows the acceleration response spectra with 5% damping ratio of the recorded near fault ground motions. Figure 2b shows the different percentiles of acceleration response spectra with 5% damping ratio illustrating that the selected earthquake ground motion records are well describing the medium to strong intensity earthquake motion histories.

Table 5.1. Characteristics of the earthquake ground motion histories

SL No	Earthquake	Year	Richter Magnitude	Epicentral Distance (km)	PGA (g)	PGV (cm/s)
1	Tabas	1978	7.4	1.2	0.922	108.0
2	Tabas	1978	7.4	1.2	0.958	103.8
3	Loma Prieta	1989	7.0	3.5	0.703	170.0
4	Loma Prieta	1989	7.0	3.5	0.458	89.3
5	Loma Prieta	1989	7.0	6.3	0.672	175.0
6	Duzce, Turkey	1999	7.1	6.3	0.728	56.44
7	Mendocino	1992	7.1	8.5	0.625	123.4
8	Mendocino	1992	7.1	8.5	0.651	91.0
9	Erzincan	1992	6.7	2	0.448	57.0
10	Landers	1992	7.3	2	0.691	133.4
11	Landers	1992	7.3	1.1	0.793	69.0
12	Nothridge	1994	6.7	1.1	0.872	171.0
13	Nothridge	1994	6.7	7.5	0.721	120.0
14	Nothridge	1994	6.7	7.5	0.583	52.9
15	Kobe	1995	6.9	6.4	1.071	157.0
16	Kobe	1995	6.9	6.4	0.563	71.0
17	Kobe	1995	6.9	3.4	0.774	170.5
18	Kobe	1995	6.9	3.4	0.686	156.7
19	Kobe	1995	6.9	4.3	0.673	129.6
20	Kobe	1995	6.9	4.3	0.736	108.4

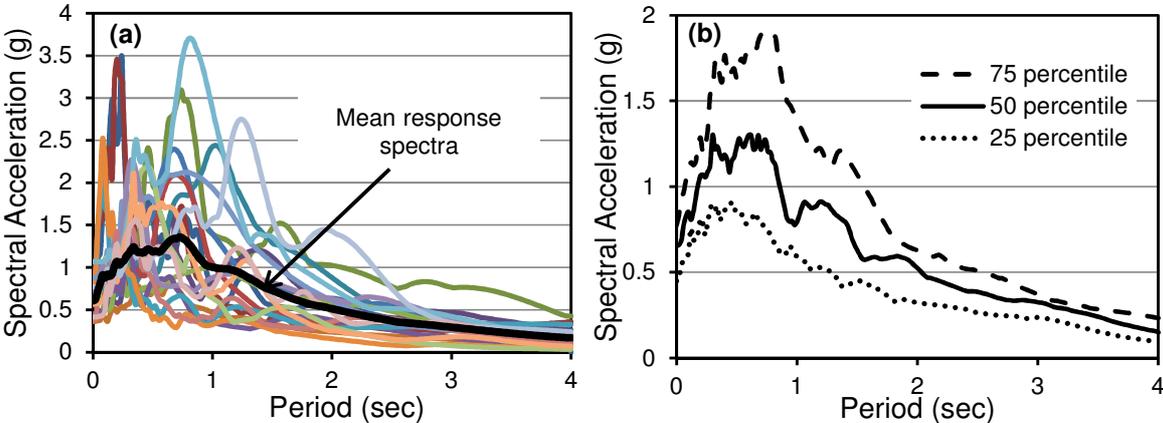


Figure 2. Earthquake ground motion records, (a) spectral acceleration, (b) percentiles of spectral acceleration of a suit of 20 near fault earthquake ground motion records

6. CHARACTERIZATION OF DAMAGE STATES

In the seismic fragility analysis, different forms of *EDPs* are used to monitor the structural responses under earthquake ground motion and measure the damage state (DS) of the bridge components. Damage states for bridges should be defined in such a way that each damage state indicates a particular level of bridge functionality. A capacity model is needed to measure the damage of bridge component based on prescriptive and descriptive damage states in terms of *EDPs* (FEMA 2003, Choi et al. 2004, Nielson 2005).

Four damage states as defined by HAZUS (FEMA 2003) are commonly adopted in the seismic vulnerability assessment of engineering structures, namely slight, moderate, extensive and collapse damages. Bridge piers are one of the most critical components, which are often forced to enter into nonlinear range of deformations under strong earthquakes. In this study, the displacement ductility of the bridge pier is adopted as damage index (*DI*). Dutta and Mander (1999) recommended five different damage states for bridge pier (Table 6.1) based on drift limits. But retrofit affects the seismic response and demand of the bridge pier and the capacity as well. For the retrofitted bridge pier new limit states need to be defined. Limit states capacities for all the two retrofitted bridge bent are obtained by transforming the drift limits proposed by Dutta and Mander (1999) to ductility demand of the bridge pier. The use of drift limits proposed by Dutta and Mander (1999) for retrofitted RC columns is well documented in literature (Shinozuka et al. 2002 and Kim and Shinozuka 2004). Both the studies used the drift limits proposed by Dutta and Mander (1999) for seismic fragility assessment of RC columns retrofitted using steel jackets. Moreover, Roy et al. (2010) experimentally investigated the seismic performance of RC bridge bent retrofitted with CFRP jacket. They found various limit states values of CFRP retrofitted bridge bent which were similar to that proposed by Dutta and Mander (1999).

Table 6.1. Damage/limit state of bridge components (adapted from Dutta and Mander, 1999)

Damage state	Description	Drift limits
Almost no	First yield	0.005
Slight	Cracking, spalling	0.007
Moderate	Loss of anchorage	0.015
Extensive	Incipient column collapse	0.025
Collapse	Column collapse	0.050

Table 6.2 shows the values of ductility demand and the corresponding damage states for the two retrofit techniques used in this study. For example, the slight damage occurs at a drift of 0.007. For CFRP jacketed pier this limit is reached when the pier encounters a displacement of 56.0mm. The yield displacement of the CFRP jacketed pier was 34.6mm. Dividing the displacement corresponding to slight damage (56.0mm) by the yield displacement (34.6mm), the ductility demand of the CFRP jacketed bridge pier for slight damage state was obtained. Following the same procedure the ductility demand of the bridge piers with ECC jacket was obtained for different damage states. Finally, the limit state capacities for the retrofitted bridge bents are presented in terms of median (S_c) and lognormal standard deviation (β_c) in Table 6.2.

Table 6.2. Ductility demand and limit state capacity of the retrofitted bridge piers

Damage state	Retrofit Techniques					
	CFRP Jacket			ECC Jacket		
	Ductility demand	Limit state capacity		Ductility demand	Limit state capacity	
S_c		β_c	S_c		β_c	
Slight	1.62	1.62	0.59	1.72	1.72	0.59
Moderate	3.47	3.47	0.51	3.70	3.70	0.51
Extensive	5.78	5.78	0.64	6.16	6.16	0.64
Collapse	11.56	11.56	0.65	12.32	12.32	0.65

In this study, the limit states of various retrofitted bridge bents are assumed to follow a lognormal distribution. There is also uncertainty associated with each median (S_c) which must be defined. This

uncertainty is given in the form of a lognormal standard deviation or dispersion (β_c). The values of lognormal standard deviation or dispersion (β_c) have been obtained following the procedure described in Nielson (2005).

7. FRAGILITY ANALYSIS OF RETROFITTED BRIDGE BENT

In this study probabilistic seismic demand models are used to derive the fragility curves. The *PSDMs* help to express the effect of a given retrofit technique on the seismic demand placed on the retrofitted bent pier. The demand parameter considered in this study is the pier displacement ductility demand. The *PSDMs* are developed by analyzing the demand placed on the retrofitted bridge bent through a regression analysis. *PSDMs* are constructed from the peak response of the bent pier obtained from the *IDA*. Figure 3 shows the *PSDMs* for retrofitted bridge bent for near field ground motions. For generating the *PSDMs* a suite of suitable ground motions representing a broad range of values for the selected *IM* (*PGA* in this study) was chosen. After the development of analytical models of retrofitted bridge bents, *IDA* was carried out. From each analysis the peak responses were calculated and plotted against the *IM* for that ground motion. Then a regression analysis was carried out to estimate a , b and $\beta_{EDP|IM}$.

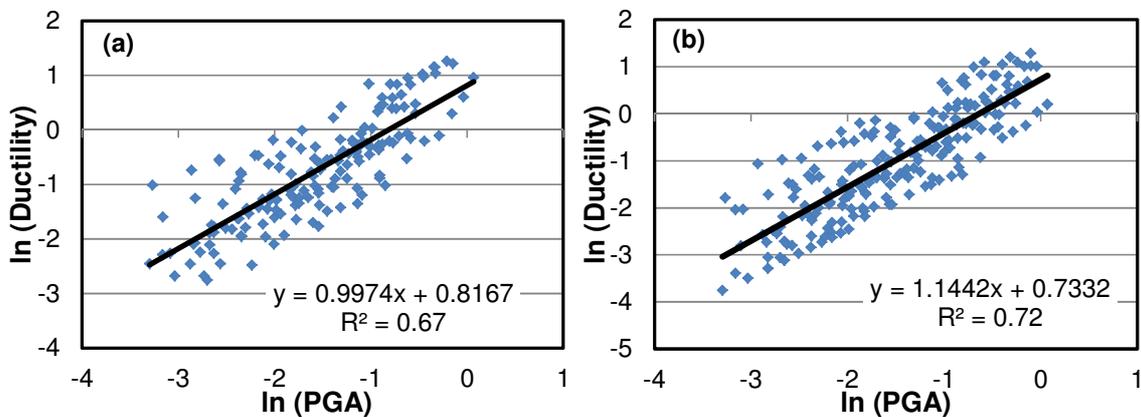


Figure 3. Comparison of the *PSDMs* for bridge bent retrofitted with (a) CFRP jacketing and (b) ECC jacketing for near fault ground motion

The impact of undertaking two different retrofit measures on the demand models is compared and presented in Table 7.1. The parameters listed represent the regression parameters from Equation 2.2 along with the dispersion. From the table it is evident that the CFRP jacketing yields an increase in the dispersion in the demand (β_{DIM}) while the ECC jacketing exhibited reduction in the dispersion in the demand. Moreover, the CFRP jacketed bridge bent tends to increase the median value of the demands placed on the piers. This is evident from the regression model as this increased the intercept ($\ln(a)$) and slope (b) of the regression model. It revealed that the ECC jacketing was more effective in reducing the demand as compared to that of the CFRP jacketing.

Table 7.1. *PSDMs* for four different retrofits of the bridge bent (near fault)

Column Ductility			
Retrofit Technique	$\ln(a)$	b	$\beta_{EDP IM}$
CFRP Jacketing	0.8167	0.9974	0.51
ECC Jacketing	0.7332	1.1442	0.48

Evaluation of the fragility curves offers a valuable insight on the effectiveness of various retrofit measures on the probability of the damage considering both the impact of retrofit on the bridge's demand and capacity. Figure 4 presents the fragility curves of the two retrofitted bridge bents under near fault ground motions. The fragility can be directly estimated from the limit state capacity of each damage state (Table 6.2) as well as the parameters for the *PSDMs* obtained from regression analysis.

Utilizing these parameters, the fragility curves were generated using equation 2.4. The figures facilitate the comparison of the relative effectiveness of two retrofit measures for the selected bridge bent. These plots of various damage state aid in expressing the effect of a retrofit measure that can vary dramatically from one damage state to another. Evaluation of the fragilities (shown in Figure 4) for the retrofitted bridge bent under near fault ground motions indicate that the CFRP jacketed bridge bent has higher probability of damage in the slight and moderate damage states while the ECC jacketed bridge bent has higher probability of collapse as compared to that of the CFRP jacketed bridge bent.

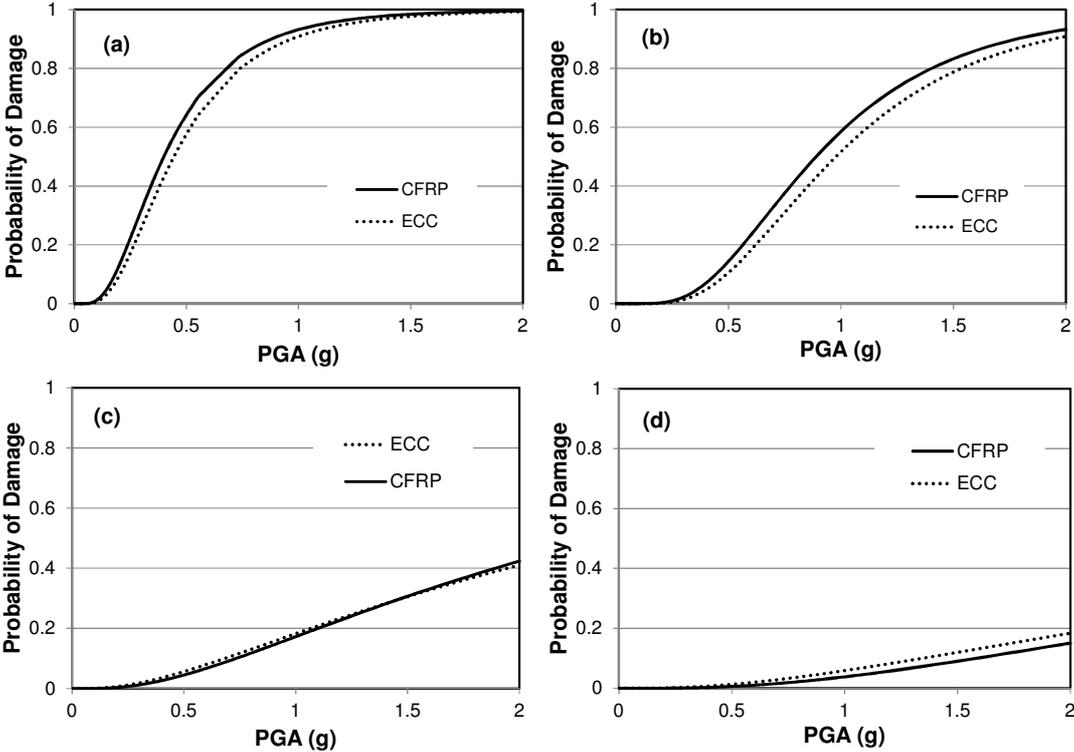


Figure 4. Fragility curves for the retrofitted bridge bents for: (a) slight damage, (b) moderate damage, (c) extensive damage, and (d) collapse, under near fault ground motion

Finally, the median of the probability of exceedance is determined for the bridge bent retrofitted with two different retrofit techniques at each damage level. Figure 5 shows a plot of the peak ground accelerations for the median values of probability of damage of the bridge bent retrofitted with two retrofit techniques under near fault ground motions.

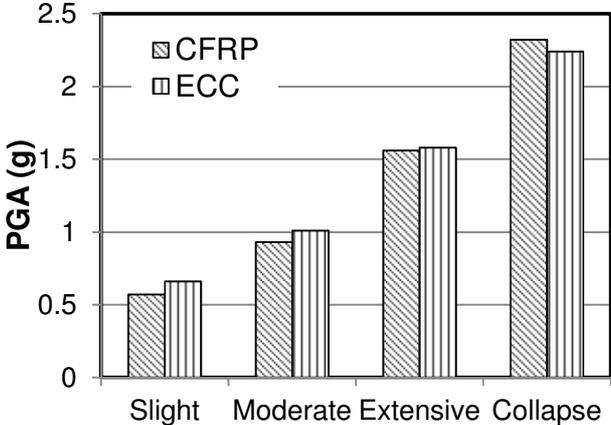


Figure 5. Comparison of median values of *PGA* for retrofitted the bridge bent

From the above figure it can be observed that the bridge bent retrofitted with CFRP jacketing portrays seismically more fragile compared to that of ECC jacketed bridge bent at slight and moderate damage state. For the slight damage state, the median *PGA* for the CFRP jacketed bent was 0.57g whereas it was 0.66g in the case of ECC jacketed bridge bent. On the other hand ECC jacketed bent was more vulnerable to collapse. While considering the collapse state, the median *PGA* for the ECC jacketed bent was 2.24 g whereas it was 2.34g in the case of CFRP jacketed bent.

8. CONCLUSIONS

This study utilizes analytical simulation method to conduct seismic fragility assessment of a multi-column bridge bent retrofitted with CFRP and ECC jacket. By using fragility functions, the impact of retrofit on the probabilistic seismic demand models and the vulnerability of the retrofitted bridge bents are evaluated. The impact of retrofit on *PSDMs* was illustrated to express the shift in ductility demand of the bridge bent resulting from the use of different retrofit measures. The fragility curves for bridge bents are generated for 20 near-fault earthquake ground motion records. Based on the analysis, the following conclusions can be drawn:

1. The numerical results show that the retrofitted bridge bents are susceptible to near fault seismic ground motions as it produced very high ductility demand on the retrofitted bridge bent.
2. The bridge bent retrofitted with CFRP jacketing portrays more vulnerability in slight and moderate damage states. On the contrary, the ECC jacketed bridge bent is more vulnerable in the collapse state.
3. Higher ductility of ECC as compared to CFRP essentially reduced the vulnerability of the ECC jacketed bridge bent considerably.
4. Analyses of the fragility curves reveal that the effectiveness of a retrofit technique in mitigating probable damage can be measured using fragility curves for a given damage state of interest.

Since the present study considers one particular type of bridge bent model without considering uncertainty in geometry and material parameters, a further study using various bridge bent models with different sets of geometry/ material properties should be conducted for better understanding the contributions of other parameters on the seismic fragility of a retrofitted bridge bent.

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REFERENCES

- Applied Technology Council and Multidisciplinary Center for Earthquake Engineering Research. (2003). Recommended LFRD guidelines for the seismic design of highway bridges. *MCEER/ATC-49*, Redwood City, California.
- Baker, J.W. and Cornell, C.A. (2006). Vector-valued ground motion intensity measures for probabilistic seismic demand analysis. *Pacific Earthquake Engineering Research report 2006/08*, PEER Center, University of California Berkeley.
- Basöz, N., Kiremidjian, A.S., King, S.A. and Law, K.H. (1999). Statistical analysis of bridge damage data from the 1994 Northridge, CA, earthquake. *Earthquake Spectra* **15**, 25-53.
- Canadian Standards Association. (2010). Canadian highway bridge design code (CAN/CSA S6-06). CSA, Toronto, Ontario.
- Choi, E., DesRoches, R., and Nielson, B.G. (2004). Seismic fragility of typical bridges in moderate seismic zones. *Engineering Structures* **26**, 187-199.

- Cornell, A.C., Jalayer, F. and Hamburger, R.O. (2002). Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines. *Journal of Structural Engineering* **128**, 526–532.
- Dutta, A. and Mander, J.B. (1999). Seismic fragility analysis of highway bridges. *Proc., Center-to-Center Project Workshop on Earthquake Engineering in Transportation Systems*, Tokyo, Japan.
- Federal Emergency Management Agency (FEMA). (2003). HAZUS-MH software. Washington DC.
- Ferracuti, B. and Savoia, M. (2005). Cyclic behaviour of FRP-wrapped columns under axial and flexural loadings. *Proc., International Conference on Fracture*, Turin, Italy.
- Filippou, F.C., Popov, E.P. and Bertero, V.V. (1983). Modelling of R/C joints under cyclic excitations. *ASCE Journal of Structural Engineering* **109:11**, 2666-2684.
- Han, T.S., Feenstar, P.S., and Billington, S.L. (2003). Simulation of highly ductile fiber-reinforced cement-based composite components under cyclic loading. *ACI Structural Journal* **100:6**, 749-757.
- Hwang .H., Jernigan, J.B. and Lin, Y.W. (2000). Evaluation of seismic damage to Memphis bridges and highway systems. *ASCE Journal of Bridge Engineering* **5**, 322-30.
- Hwang, H., Liu, J.B. and Chiu, Y.H. (2001). Seismic fragility analysis of highway bridges. *Mid-America Earthquake Center report: project MAEC RR-4*. Urbana: MACE.
- Kim, S.H. and Shinozuka, M. (2004). Development of fragility curves of bridges retrofitted by column jacketing. *Probabilistic Engineering Mechanics* **19**,105–112.
- Mackie, K.R. and Stojadinović, B. (2004). Fragility curves for reinforced concrete highway overpass bridges. *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, BC, Canada.
- Madas, P., and Elnashai, A.S. (1992). A new passive confinement model for transient analysis of reinforced concrete structures. *Earthquake Engineering and Structural Dynamics* **21**,409-431.
- Menegotto, M. and Pinto, P.E. (1973). Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behaviour of elements under combined normal force and bending. *Symposium on the Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads*, International Association for Bridge and Structural Engineering, Zurich, Switzerland, 15-22.
- Nielson, B.G. (2005). Analytical Fragility Curves for Highway Bridges in Moderate Seismic Zones. Ph.D. thesis, Georgia Institute of Technology, Atlanta.
- Padgett, J.E. and DesRoches, R. (2008). Methodology for the development of analytical fragility curves for retrofitted bridges. *Earthquake Engineering and Structural Dynamics* **37**, 157-74.
- Pantelides, C.P. and Gergely, J. (2002). Carbon-fiber-reinforced polymer seismic retrofit of RC bridge bent: design and in situ validation. *Journal of Composites for Construction* **6:1**, 52-60.
- Roy, N., Paultre, P., and Proulx, J. (2010). Performance based seismic retrofit of a bridge bent: Design and experimental validation. *Can. J. Civ. Eng.* **37**, 367-379.
- Seismostruct V5.0.5 (2010) www.seismosoft.com.
- SAC Steel Project. (2000). 1301 S. 46th Street, Richmond, CA 94804-4698. Available at: http://nisee.berkeley.edu/data/strong_motion/sacsteel/motions/nearfault.html. Accessed: August 12, 2011.
- Shinozuka, M., Feng, M.Q., Lee, J. and Naganuma, T. (2000a). Statistical analysis of fragility curves. *ASCE Journal of Engineering Mechanics* **126**, 1224-31.
- Shinozuka, M., Kim, S.H., Kushiya, S. and Yi, J.H. (2002). Fragility curves of concrete bridges retrofitted by column jacketing. *Earthquake Engineering and Engineering Vibration* **1:2**, 195-205.
- Somerville, P.G. (2002). Characterizing near fault ground motion for the design and evaluation of bridges. *Proc., Third National Conference and Workshop on Bridges and Highways*. Portland, Oregon.
- Spoelstra, M. and Monti, G. (1999). FRP-confined concrete model. *Journal of Composites for Construction, ASCE* **3**, 143-150.
- Swensen, S. and Wong, K. (2011). Evaluation of peak structural responses based on consistent elastic and inelastic design spectra. *Struct. Design Tall Spec. Build.*, **20**, 164–176.
- Yamazaki, F., Motomura, H. and Hamada, T. (2000). Damage assessment of expressway networks in Japan based on seismic monitoring. *Proc. of 12th World Conference on Earthquake Engineering*, Paper No. 0551.
- ZEUS NL. (2011). A system for inelastic analysis of structure. V-1.9.0, Mid America Earthquake Centre. http://mae.cee.uiuc.edu/software_and_tools/zeus_nl.html.
- Zhang, J. and Huo, Y. (2009). Evaluating effectiveness and optimum design of isolation devices for highway bridges using the fragility function method. *Engineering Structures* **31**, 1648-1660.