Bridge Functionality Relationships for Improved Seismic Risk Assessment of Transportation Networks

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Relationships between bridge damage and the resulting loss of functionality of the bridge are critical to assessing the impact of an earthquake event on the performance of the transportation network. This study addresses this data need by use of a Web-based survey of central and southeastern U.S. Department of Transportation bridge inspectors and officials. Results of the 28 responses are analyzed and offer a link between various types of bridge component damage and the expected level of allowable traffic carrying capacity due to closure decisions and repair procedures. This data is utilized to assess the probability of meeting various damage states, expressed in terms of restoration of functionality, and subsequently facilitate the refinement of component limit-state capacities for analytical fragility curve development. The bridge functionality relationships and methodology outlined serve as the basis for refinement of critical tools in the seismic risk assessment framework and improved assessment of transportation network performance.

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INTRODUCTION

Seismic risk assessment (SRA) is becoming a more prevalent approach for estimating the potential impact of an earthquake event on an affected region. Several researchers in the field of lifeline earthquake engineering have presented SRA methodologies for transportation systems (Kiremidjian et al. 2002, Chang et al. 2000, Werner et al. 1997). These methodologies outline similar frameworks for assessing disruptions to transportation networks, leading to estimates of distributed damage in the network, restricted access of emergency routes, as well as economic losses due to reduced traffic flow. The general procedure for assessing the consequences of a seismic event includes defining the system and region of interest, simulating a deterministic ground motion or probabilistic hazard, assessing the performance of individual components (bridges), assigning associated levels of functionality to the bridges and roads, performing a network analysis and simulated traffic flow, and assessing the losses. While this approach has many potentially viable and beneficial applications, it relies heavily on the availability and reliability of incorporated tools and data.

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Significant work has been performed in assessing the potential seismic response of bridges and expected level of damage, often expressed as vulnerability or fragility curves (Shinozuka 2000, Hwang et al. 2000b, Choi et al. 2004). However, one of the critical data needs is the relationships between extent of damage to a bridge and the resulting loss-of-functionality of the network component. This is essential to understanding the consequences of an earthquake event. This functionality is often a result of closure decisions made by post-earthquake inspectors, as well as the procedures for repair of the bridge. While there has been limited previous research in the area, relationships between bridge damage and functionality provide essential data for various components of the SRA framework. Such relationships are essential for modeling potential decisions of bridge inspectors following an event and the anticipated allowable traffic carrying capacity of bridges and roadways, as well as for refining the limit states for bridge fragility curve development such that these limit states for different components have a similar implication in terms of overall bridge system functionality and allowable traffic carrying capacity.

Currently, very little information linking bridge damage and subsequent functionality exists. These relationships may be developed through assimilation of empirical data from past earthquake events; however, this information is limited even in regions of high seismicity, such as parts of the West Coast, and is altogether lacking for the central and southeastern United States (CSUS) region. Analytical approaches to developing these relationships have been investigated for bridges that are typical in California (Mackie and Stojadinovic 2004), and are more prescriptive in the fact that they serve to indicate the available load carrying capacity of the bridge. While this is valuable information, the intent of this research is to capture the anticipated decisions by inspectors and investigate damage to various components of typical CSUS bridges.

An alternate approach to gathering information relating bridge damage to functionality is the use of expert opinion. The FEMA-funded ATC-13 project recognized the need for this data in California and attempted to gather data on loss of function and restoration time for lifeline facilities (ATC 1985). The survey participants were queried as to the number of days elapsed before restoring 30%, 60%, and 100% functionality for a given damage state. Although there were only four respondents to the bridge survey, HAZUS uses this data to provide discrete and continuous curve fits to the ATC-13 responses (FEMA 1999). Hwang et al. performed an initial study on bridge repair sequencing and downtime in mid-America through a survey of DOT and consulting engineers (Hwang et al. 2000a). Hwang presented four descriptive damage states for a continuous multispan concrete girder bridge supported on multicolumn bents and reported potential repair strategies, estimated percent replacement costs, and stepwise functionality restoration curves. This expert opinion survey received nine responses and indicated the need for follow-up investigation.

METHODOLOGY

The advantage of the expert opinion method for developing bridge damage-functionality relationships is its ability to capture the subjective nature of bridge functionality and closure decisions. While significant uncertainty exists in the closure and repair decisions following an earthquake event, eliciting the opinions of those who will be called upon to make those subjective decisions helps to most appropriately model potential decision making and estimate allowable levels of bridge traffic carrying capacity. Targeting respondents in the region of interest (central and southeastern United States) provides results indicative of the regional dependence of the relationships. For the above-stated reasons, the expert opinion method has been adopted for this study. This research addresses the need for development of relationships between bridge damage and functionality by use of a Web-based survey that elicits expert opinion data on the expected levels of allowable traffic carrying capacity and repair measures for various types and levels of bridge damage.

WEB-BASED SURVEY

The survey has been devised considering the technical language and approach common to CSUS inspectors, using recommended principles for Web survey development by researchers in the field, and through iteration in coordination with officials from the Central U.S. Earthquake Consortium (CUSEC) Transportation Task Force. Key considerations included, but are not limited to, the following:

- Clearly conveying the questions and information requested.
- Using visuals to relate bridge damage descriptions to physical and meaningful events.
- Balancing the need for comprehensive data collection with reasonable survey response length.
- Careful utilization of the capabilities of Internet technologies and Web survey formats such that convenience, understanding, and response accuracy are maximized.

Dillman has performed extensive research in the field of survey development, expert opinion solicitation, and Web survey design. Many of the findings from Dillman's and Smyth's research and the principles recommended for construction of Web surveys have been implemented. Some examples include effective use of fonts, spacing, and grouping; providing instructions on necessary computer actions; and allowing respondents to skip questions and allowing them to answer out of order (Dillman et al. 1998a, b; Smyth et al. 2004). In general, implementation of these principles among others has helped to produce a more respondent-friendly Web survey regarding bridge damage functionality.

Post-earthquake inspection manuals from CSUS DOTs, namely, the Indiana *Handbook for the Post-Earthquake Safety Evaluation of Bridges and Roads* (INDOT 2000) and the Missouri *Post Incident Bridge Inspection Training* manual (MODOT 2004) were reviewed for consistent terminology and organization of the survey. The component damage questions were posed in the same sequence as a bridge inspector is instructed to evaluate a bridge, and using similar quantitative and visual descriptions as are presented in inspection training and field guides. The clarity and comprehensibility of instructions and question format were refined with CUSEC members' input, and the length of the survey was revised to achieve an anticipated increased level of response.

SURVEY AND RESPONSES ELICITED

The Web-based survey queried DOT officials and consulting engineers as to the expected level of traffic carrying capacity of a bridge over time, given a level of bridge component damage. Multispan continuous and multispan simply supported bridges were addressed and the results are expected to be extracted to single-span bridges through consideration of the appropriate components. Damage considered includes the approach and abutments, superstructure/bearings, columns in single- and multicolumn bents, and footings. For each component, various levels of damage were presented in quantitative or qualitative terms, and photos from past earthquake damage that correspond with the given level of damage were offered as an illustrative example. The respondents were asked to provide the expected traffic carrying capacity at time 0, 1, 3, 7, and 30 days following an event that may result from closure decisions, traffic restrictions, repair, and restoration. The respondents were also asked to select a potential repair measure that would be executed for the given level of component damage. A screen shot from the Web-based survey is shown in Figure 1a, with an example of a completed table for one section of the survey (Figure 1b). The full survey may be viewed at http://www.ce.gatech.edu/research/maecenter/jamies_webs/myweb6/jamie's%20index.htm.

As with previous expert opinion surveys, the respondents were asked to assume a given set of conditions. The assumptions for this response data are as follows:

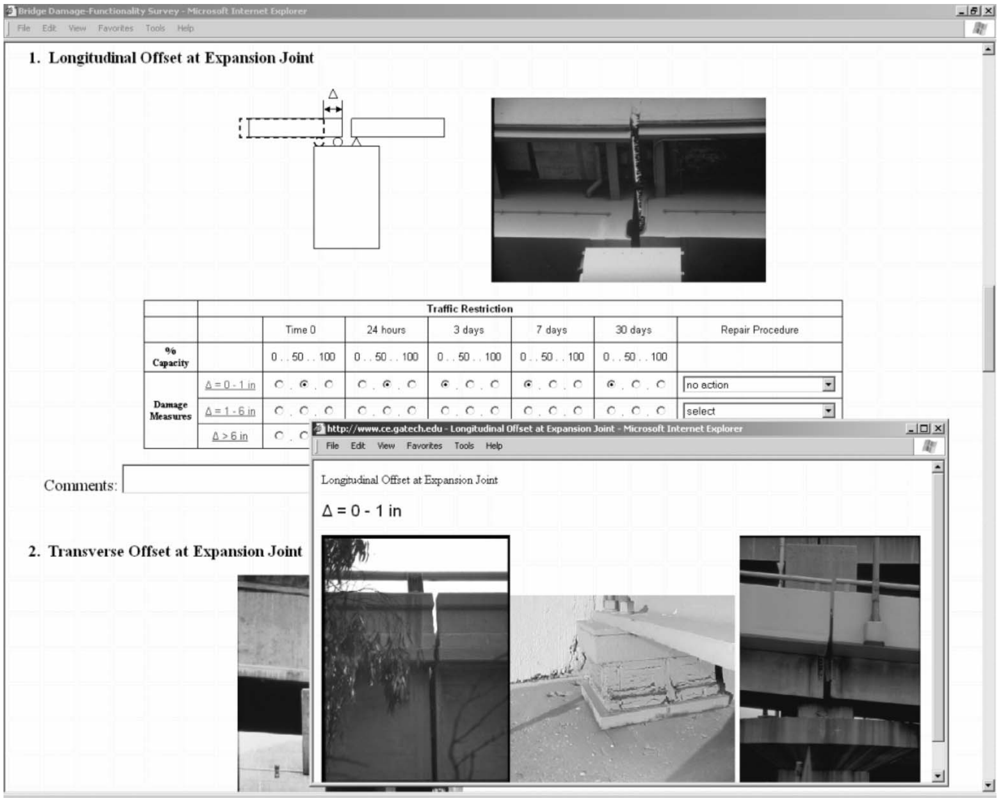
- Assume the typical post-disaster level of funding and resources are available for repair.
- Consider current best practices for repair procedures.
- Consider only the effect of the component of interest on the traffic restrictions and resulting bridge functionality.

ANALYSIS AND RESULTS OF EXPERT OPINION SURVEY

A contact person was identified at nine central and southeastern U.S. DOTs and asked to distribute the survey to three to five persons in the bridge engineering, maintenance, and operations departments. Two consultants who were identified as close collaborators in post-event inspection and repair were also included. Twenty-eight respondents from nine states in the CSUS region participated in the Web survey. The states represented include Arkansas, Georgia, Illinois, Indiana, Kentucky, Mississippi, Missouri, South Carolina, and Tennessee. While the overall response rate may not be directly computed, an estimate is determined based on knowledge of the response rate from a subset of the sample, indicating that the response rate is on the order of 75%.

PROBABLE ALLOWABLE TRAFFIC CARRYING CAPACITY

The results of the bridge damage-functionality survey may be presented in the form of functionality probability matrices (FPMs). The matrices directly represent the results



1. Longitudinal Offset at Expansion Joint

	Traffic Restriction						
		Time 0	24 hours	3 days	7 days	30 days	Repair Procedure
% Capacity		0 . . 50 . . 100	0 . . 50 . . 100	0 . . 50 . . 100	0 . . 50 . . 100	0 . . 50 . . 100	
Damage Measures	Δ = 0 - 1 in	○ . ● . ○	○ . ● . ○	● . ○ . ○	● . ○ . ○	● . ○ . ○	no action
	Δ = 1 - 6 in	○ . ○ . ○	○ . ○ . ○	○ . ○ . ○	○ . ○ . ○	○ . ○ . ○	select
	Δ > 6 in	○ . ○					

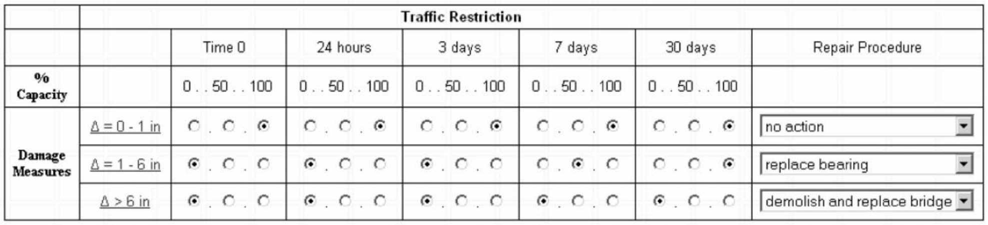
Comments:

2. Transverse Offset at Expansion Joint

Longitudinal Offset at Expansion Joint

Δ = 0 - 1 in

(a)



	Traffic Restriction						
		Time 0	24 hours	3 days	7 days	30 days	Repair Procedure
% Capacity		0 . . 50 . . 100	0 . . 50 . . 100	0 . . 50 . . 100	0 . . 50 . . 100	0 . . 50 . . 100	
Damage Measures	Δ = 0 - 1 in	○ . ○ . ●	○ . ○ . ●	○ . ○ . ●	○ . ○ . ●	○ . ○ . ●	no action
	Δ = 1 - 6 in	● . ○ . ○	● . ○ . ○	● . ○ . ○	○ . ● . ○	○ . ○ . ●	replace bearing
	Δ > 6 in	● . ○ . ○	● . ○ . ○	● . ○ . ○	● . ○ . ○	● . ○ . ○	demolish and replace bridge

(b)

Figure 1. (a) Screen capture of Web-based damage-functionality survey with hyperlink opened for additional photos longitudinal offset of 0–1″ from past earthquake events. (b) Example responses for one section of the survey, eliciting expected level of allowable traffic carrying capacity (%) for various levels of damage and times following the earthquake.

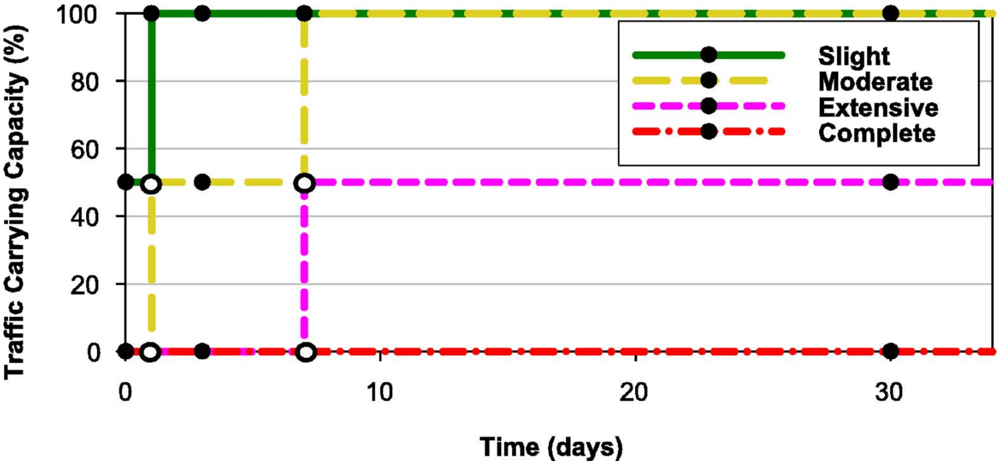


Figure 2. Stepwise restoration functions defining slight through complete damage.

of the survey and provide the percent of respondents that indicate a given level of component damage would result in a specific level of allowable traffic carrying capacity over time:

$$P[X = x | D = d \cap T = t] \tag{1}$$

where X is the allowable traffic carrying capacity, D is the level of damage to the component of interest, and T is the time following the earthquake event. Examples of the FPMs are listed in Table 1 for settlement of the approach at the approach/abutment interface, transverse offset of the deck at the expansion joint, and column damage in a single-column bent.

As evidenced by Table 1, the trends parallel what one might deduce from intuitive reasoning. Increased damage to a component often leads to a higher probability of reduced functionality, and the probability for full (100%) capacity tends to increase over time. In general, the results showed that the variance in responses decreased over time for the lower levels of damage and increased over time for the higher levels of damage. This indicates that for a larger level of component damage, there is more uncertainty in the expected level of allowable traffic carrying capacity of the bridge as time progresses following the event, while for smaller levels of damage the uncertainty in capacity is at its highest level immediately following the event and decreases over time.

DAMAGE STATE PROBABILITIES

One application of the results of the damage-functionality survey is in quantifying the probability of having a given restoration function, or capacity over time. In essence, the restoration functions themselves become definitions of various damage states, where, for example, slight damage corresponds to a particular restoration. The definitions of damage states for slight, moderate, extensive, and complete damage used in this analysis

Table 1. Functionality probability matrices for various types of bridge damage

Settlement of Approach at Approach/Abutment Interface

Damage, d	**0–1″**					**1–6″**					**>6″**				
Time, t (days)	**0**	**1**	**3**	**7**	**30**	**0**	**1**	**3**	**7**	**30**	**0**	**1**	**3**	**7**	**30**
$\mathbf{P[X=0\%\mid D=d\cap T=t]}$	0.107	0.036	0.036	0.036	0.036	0.357	0.185	0.036	0.000	0.000	0.857	0.500	0.250	0.071	0.036
$\mathbf{P[X=50\%\mid D=d\cap T=t]}$	0.179	0.071	0.036	0.036	0.036	0.500	0.370	0.286	0.036	0.036	0.143	0.250	0.357	0.321	0.071
$\mathbf{P[X=1000\%\mid D=d\cap T=t]}$	0.714	0.893	0.929	0.929	0.929	0.143	0.444	0.679	0.964	0.964	0.000	0.250	0.393	0.607	0.893

Transverse Offset at Expansion Joint

Damage, d	**0–1″**					**1–6″**					**>6″**				
Time, t (days)	**0**	**1**	**3**	**7**	**30**	**0**	**1**	**3**	**7**	**30**	**0**	**1**	**3**	**7**	**30**
$\mathbf{P[X=0\%\mid D=d\cap T=t]}$	0.107	0.036	0.000	0.000	0.000	0.571	0.464	0.286	0.107	0.036	0.857	0.750	0.643	0.464	0.286
$\mathbf{P[X=50\%\mid D=d\cap T=t]}$	0.214	0.179	0.179	0.107	0.071	0.179	0.214	0.321	0.286	0.250	0.071	0.143	0.107	0.179	0.036
$\mathbf{P[X=100\%\mid D=d\cap T=t]}$	0.679	0.786	0.821	0.893	0.929	0.250	0.321	0.393	0.607	0.714	0.071	0.107	0.250	0.357	0.679

Damage to Column (Single-Column Bent)

Damage, d	**Cracking**					**Spalling**					**Rebar Buckle/Fracture/Pullout**				
Time, t (days)	**0**	**1**	**3**	**7**	**30**	**0**	**1**	**3**	**7**	**30**	**0**	**1**	**3**	**7**	**30**
$\mathbf{P[X=0\%\mid D=d\cap T=t]}$	0.370	0.222	0.148	0.148	0.074	0.750	0.607	0.429	0.250	0.143	0.964	0.929	0.821	0.750	0.500
$\mathbf{P[X=50\%\mid D=d\cap T=t]}$	0.148	0.259	0.259	0.185	0.074	0.179	0.250	0.393	0.250	0.143	0.000	0.000	0.143	0.107	0.036
$\mathbf{P[X=100\%\mid D=d\cap T=t]}$	0.482	0.519	0.593	0.667	0.852	0.071	0.143	0.179	0.500	0.714	0.036	0.071	0.036	0.143	0.464

are those types and levels of damage that correspond to the stepwise restorations shown in Figure 2. For example, slight damage indicates damage resulting in capacity reduced to 50% following the earthquake event, yet fully restored in approximately 1 day. Complete damage, however, refers to damage leading to closure of the bridge, and still having 0% capacity 30 days after the event. The probability of having a capacity that is less than or equal to the damage state definition for a given type and level of damage can then be assessed through analysis of the damage-functionality survey results. This results in an assessment of whether or not the damage state definitions were exceeded, by evaluating the functionality over time. These damage state exceedance probabilities are found as the probability of an intersection of events along the restoration timeline, as shown in Equation 2:

$$P[DS \geq ds_i | D = d] = P\left[\bigcap_i X_t \leq x_{t,i}\right] \tag{2}$$

where DS is the damage state; ds_i is the damage state of interest; D is the level of component damage; d is the realization of that component damage expressed as a range of values for our data set; X_t is the allowable traffic carrying capacity at time t, where $t = \{0, 1, 3, 7, 30\}$days; and $x_{t,i}$ is the definition of capacity at time t for damage state i. For example, this conditional probability would be expressed as shown in Equation 3 for moderate damage given transverse offset at the expansion joints of $0-1''$.

$$P[DS \geq Moderate | D = 0 - 1''] = P\lfloor X_{t=0} \leq 0\,\% \cap X_{t=1} \leq 50\,\% \cap X_{t=3} \leq 50\,\% \cap X_{t=7} \leq 100\,\% \cap X_{t=30} \leq 100\,\% \rfloor \tag{3}$$

Analysis of the 28 survey responses allows for an estimation of the probability of meeting or exceeding a given damage state, where the intersection of events expressed in Equation 2 is evaluated for each survey respondent in order to assess the damage state exceedance probability. Example conditional probabilities for the potential of meeting or exceeding a damage state as defined in Figure 2, given a level of damage to the bridge, are shown in Table 2. The Appendix (Table A1) contains the set of damage state exceedance probabilities for the remaining types of damage investigated in the survey. These conditional damage state probabilities represent the cumulative distributions over the levels of damage investigated. The results of this analysis offer a critical link between the level of damage to bridge components and the damage states defined in terms of allowable traffic carrying capacity. In deriving the exceedance probabilities, an assumption is made that the survey responses reflect the expected post-earthquake decisions affecting bridge functionality. The authors acknowledge that other social, political, or economic factors may indeed impact the restoration as well. A particular application of the exceedance probabilities given various levels of bridge component damage will be illustrated in the next section.

USE OF SURVEY DATA FOR ASSESSING LIMIT STATE CAPACITIES FOR BRIDGE FRAGILITY CURVE DEVELOPMENT

One of the tools that is essential for assessing the seismic risk to a regional transportation network is bridge fragility curves. They facilitate evaluation of the expected

Table 2. Damage state exceedance probabilities for given levels of damage

Settlement of Approach at Approach/Abutment Interface				
	$P[DS \geq ds \mid D = d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0–1″	0.286	0.036	0.036	0.036
1–6″	0.889	0.148	0.000	0.000
>6″	1.000	0.464	0.214	0.071
Transverse Offset at Expansion Joint				
	$P[DS \geq ds \mid D = d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0–1″	0.321	0.036	0.000	0.000
1–6″	0.750	0.429	0.214	0.107
>6″	0.929	0.714	0.536	0.464
Damage to Column (Single-Column Bent)				
	$P[DS \geq ds \mid D = d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
Cracking	0.519	0.185	0.148	0.148
Spalling	0.929	0.607	0.286	0.250
Rebar buckle/fracture/pullout	0.964	0.929	0.786	0.750

seismic performance of a bridge. Fragility curves indicate the probability of the bridge being damaged beyond a given state for various levels of ground motion intensity. This fragility expressed as a conditional probability is as follows:

$$Fragility = P[DS \mid IM = y] \tag{4}$$

where *DS* is the damage state or bridge performance, *IM* is the intensity measure of the ground motion, and *y* is the realization of the ground motion intensity. In the context of performance-based earthquake engineering, damage states are defined as the condition of the system or component of interest. These damage states are often related to performance objectives for the structure, and Ellingwood and Wen indicate the need for these objectives to be related to economic losses or opportunity losses for some systems (2005). Key objectives for bridges, as critical nodes in the transportation network, are their states of functionality following an event. Thus appropriate damage states for bridges may be defined such that the component damage for each damage state is indicative of a level of bridge functionality, as presented in the previous section for slight through complete damage.

The limit states, or structural capacities (S_c), for estimating bridge fragility are quantitative measures of bridge or component performance, and should have a relation to the functionality or overall operation and performance of the bridge, referred to here as the damage state. These limit states shall be mappable to the level of response or demand (S_D) placed on the structure, often referred to as an engineering demand parameter (EDP), in order to facilitate evaluation of the fragility as expressed in Equation 5:

$$Fragility = P\left[S_D \geq S_C \middle| IM\right] \tag{5}$$

Traditionally, researchers have considered the demand placed on a single bridge component, such as the columns, using engineering demand parameters of drift or column ductility (Shinozuka 2000, Hwang et al. 2000b). As analytical methods for evaluation of the bridge fragility are maturing, the contribution of other vulnerable components (e.g., bearings, abutments) to the bridge fragility have been recognized and considered (Choi et al. 2004). However, it is essential that the limit states for different components have a similar meaning in terms of the overall bridge performance, expressed as its functionality. The challenge is to assess, for example, the limit states that result in slight damage to the columns and slight damage to the bearings affecting the performance of the bridge in an analogous way. One approach for doing so is to scale the component limit states such that their achievement has an equivalent meaning in terms of the impact on bridge functionality resulting from inspection and closure decisions. These functionally consistent limit states may be derived through evaluation of judgmental data, such as that collected from the survey discussed above, to assess the limits that bridge inspectors and officials place on damage before the functionality is expected to be affected.

EXAMPLE LIMIT-STATE EVALUATION USING SURVEY RESULTS

Fragilities are often modeled by a lognormal cumulative distribution function, where the structural demand and capacity are assumed to be lognormally distributed (Hwang and Jaw 1990). This assumption conveniently leads to a closed form solution for the fragility, as given in Equation 6 (Melchers 1999):

$$P_f = \Phi\left(\frac{\ln(m_{s_c}/m_{s_d})}{\sqrt{\beta^2_{D|IM} + \beta^2_C}}\right) \tag{6}$$

where m_{Sc} and m_{Sd} are the median values of structural capacity and the median value of structural demand, respectively; β_C and $\beta_{\mathrm{D|IM}}$ are the associated lognormal standard deviations, or dispersions, of capacity and demand, respectively; and $\Phi(\bullet)$ is the standard normal cumulative distribution function. The median value of structural capacity, m_{Sc}, is often referred to as the limit state capacity, as defined above.

To facilitate such an assessment of fragility, an example of the use of the survey data for deriving functionally consistent limit states is performed, maintaining the common assumption of a lognormal distribution of capacity. It is recognized that the use of such data introduces subjectivity into the assessment of structural capacity, along with significant uncertainty; however, this type of approach attempts to model what may actually occur following an event and the impacts of human decisions regarding closure and repair.

A lognormal probability plot is constructed for parameter estimation, noting that the percentiles of the cumulative distributions, F_x, for various components at each of the four damage states were derived previously, as shown in Table 2. It is noted that several assumptions must be made, such as selecting representative values for the ranges given (e.g., $0.5''$ for the range $\Delta = 0 - 1''$). Also, the damage state probabilities of 0 and 100% were plotted at a cumulative probability of $0 + 0.5/n$ and $1 - 0.5/n$, where n is the number of respondents. This recognizes the lack of complete certainty one can have in the probability of meeting or exceeding a damage state, as is similarly reflected in various proposed rank means, or cumulative probability plotting positions (Cacciari 1991). Linear regression of the following form:

$$\ln(x) = \hat{\lambda}_x + \hat{\zeta}_x \cdot \Phi^{-1}(F_x) \tag{7}$$

yields an estimate of the lognormal parameters, λ_x and ζ_x, of the underlying distribution. An example is shown in Figure 3a for the regression on *transverse offset at the expansion joint*, and the corresponding plot of the cumulative distribution function for each damage state is shown in Figure 3b. Recalling that the median value of a lognormal distribution is

$$x_m = e^{\lambda_x} \tag{8}$$

we can use the findings of the regression to report the limit state capacities in terms of the traditional median and dispersion, m_{Sc} and β_C, as listed in Table 3.

These limit states correspond to the damage state definitions shown in Figure 2. It should be noted, however, that the actual implementation of these limit states for use in fragility analysis is dependent on their mapping into measurable quantities analytically. For example, the limit states derived for transverse offset at the expansion joint may be mapped by either monitoring the transverse offset as the engineering demand parameter, or the deformation of the bearings at the expansion joint. However, some mapping is more abstract, as is the case with columns, where the survey data and percentiles of the cumulative distribution function correspond to cracking, spalling, and bar buckling. The mapping of such physical phenomena to an engineering demand parameter is dependent upon the seismic detailing, geometry, and parameters specific to the bridge of interest, and may be strengthened through assessment of empirical data from experimental testing of similar components, as discussed by Mackie and Stojadinovic (2004).

Regardless of the mapping strategy adopted, the conceptual objectives remain the same: to derive the limit state capacities of various components for slight through complete damage such that they have a functionally consistent implication in terms of the effect on the operation level of the bridge. This link between the damage to the bridge and functionality is provided by the damage state exceedance probabilities, or percentiles of the cumulative distribution, that were derived through assessment of the survey data. Through this type of approach, the limit state capacities are more meaningful in terms of bridge performance objectives, and the limit states for various components have a consistent meaning for a given damage state.

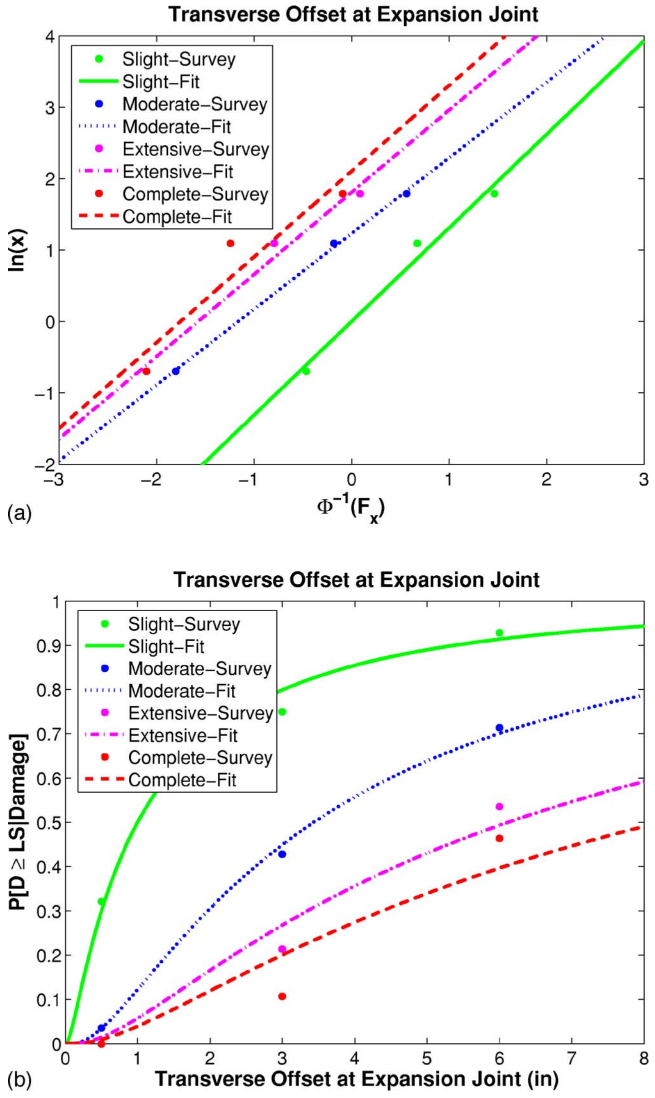


Figure 3. Lognormal probability plot for estimating the lognormal parameters of transverse offset at the expansion joint (a), and the corresponding cumulative distribution function for each damage state compared to the percentiles from the survey data analyses (b).

CONCLUSIONS

This study has targeted the need for data to relate the effects of bridge component damage to the functionality of the bridge, expressed as allowable traffic carrying capacity. In order to model the potential decisions and the subjective nature of this problem, an expert opinion survey was utilized. The design considerations, excerpt of the survey

Table 3. Limit state capacities expressed as the median and dispersion for a lognormal fit of transverse offset at expansion joint

Damage	**Median, m_{Sc} (in.)**	**Dispersion, β_C**
Slight	1.00	1.31
Moderate	3.43	1.06
Extensive	6.11	1.15
Complete	8.21	1.20

tools, assumptions, and target respondents are presented to give the context of the survey methodology. Analysis of the 28 survey responses indicates that the relationship between the level of bridge component damage and allowable capacity due to closure and repair decisions followed trends of logical deduction. These results were then utilized to derive damage state exceedance probabilities for various types of bridge component damage, where the damage states were presented in terms of allowable traffic carrying capacity, or restoration of functionality. These stepwise restoration functions indicate a definition of damage states that are meaningful in terms of performance objectives for bridges as components of the transportation network. The damage state exceedance probabilities serve as a critical link between component damage and anticipated bridge functionality. Their use in assessing limit state capacities for bridge components was presented for deriving functionally consistent limit states for use in next generation fragility curve development. These fragility curves may then be inherently associated with a level of functionality based on the damage state definitions.

While this study focused on the central and southeastern United States, the methodology is applicable to other regions. An approach is offered by which the visible damage to a bridge may be related to its functionality, reflective of the opinions of those who would be making those decisions, and that targets the refinement of component limit states such that they have similar implications as to bridge functionality and performance. The data collected from the survey and approach outlined serves as the basis for refinement of critical tools in the SRA framework, including bridge fragility curves and restoration functions for input to transportation network models. These tools are essential for estimating the impact of an earthquake event on the performance of the transportation network and associated consequences.

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APPENDIX

Table A1. Damage state exceedance probabilities for given remaining types of bridge damage

Settlement of Approach at Approach/Abutment Interface

	$P[DS \geq ds \mid D=d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0−1”	0.286	0.036	0.036	0.036
1−6”	0.889	0.148	0.000	0.000
>6”	1.000	0.464	0.214	0.071

Damage to Abutment

	$P[DS \geq ds \mid D=d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
Cracking	0.536	0.071	0.036	0.000
Spalling &/or Rotation	0.821	0.393	0.250	0.107

Longitudinal Offset at Expansion Joint

	$P[DS \geq ds \mid D=d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0−1”	0.179	0.000	0.000	0.000
1−6”	0.893	0.250	0.143	0.143
>6”	1.000	0.750	0.643	0.536

Vertical Offset at Expansion Joint

	$P[DS \geq ds \mid D=d]$			
Damage,d	**Slight**	**Moderate**	**Extensive**	**Complete**
0−1”	0.429	0.036	0.036	0.036
1−6”	1.000	0.482	0.259	0.222
>6”	1.000	0.778	0.593	0.407

Longitudinal Offset Over Pier

	$P[DS \geq ds \mid D=d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0−1”	0.250	0.071	0.071	0.036
1−6”	0.857	0.393	0.286	0.143
>6”	0.964	0.714	0.536	0.429

Damage to Column (Multi-Column Bent – One Column Damaged)

	$P[DS \geq ds \mid D=d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0−1”	0.500	0.107	0.036	0.036
1−6”	0.857	0.464	0.179	0.143
>6”	0.964	0.714	0.607	0.571

Separation of Soil from Footings

	$P[DS \geq ds \mid D=d]$			
Damage, d	**Slight**	**Moderate**	**Extensive**	**Complete**
0−3”	0.346	0.115	0.077	0.039
>3”	0.692	0.308	0.192	0.154

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