Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No

BRIDGE BEARING FUSE SYSTEMS FOR REGIONS WITH HIGH-MAGNITUDE EARTHQUAKES AT LONG RECURRENCE INTERVALS

E. T. Filipov[1], J. S. Steelman[1], J. F. Hajjar[2], J. M. LaFave[3], and L. A. Fahnestock[4]

ABSTRACT

This paper describes an ongoing experimental and computational program investigating bridge bearing assemblies common in mid-America, to ascertain their effectiveness as seismic fuses and to characterize their component behavior during large displacements of the superstructure. The bearing assemblies considered in the testing program are intended to address seismic risk for regions where the hazard is dictated by infrequent, but large magnitude, seismic events such as may occur in the New Madrid seismic zone near southern Illinois. Test specimens include low-profile fixed bearings, as well as steel-reinforced elastomeric bearings. The elastomeric bearings, some of which include a Teflon-on-steel sliding surface, have stiffened L-shaped retainer brackets to restrain transverse response at service load levels. The bearing components being studied are intended to ensure predictable, elastic response for service loading, including small seismic events. However, for larger seismic events, mechanical response of these bridge bearings will transition through highly nonlinear mechanisms that require a refined behavioral understanding, including post-yield deformations and fracture of selected steel components in the fixed bearings, high shear strain response in the elastomer, and sliding along predetermined interfaces. The experimental program is evaluating potential fuse mechanisms and component behavior that will then be implemented in computational models of complete bridges to assess global system response. The research will develop comprehensive test data upon which to base bridge design guidelines for proportioning fuse components to provide reliable service performance, as well as a passive, quasi-isolated global response during a major seismic event. This design dichotomy of bridge response ensures seismic safety (i.e., prevention of span loss) while maintaining appropriate fiscal responsibility consistent with the nature of seismic risk in regions where major earthquakes are expected to occur only at long recurrence intervals.

---

[1] Graduate Research Assistant, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801

[2] Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801

[3] Associate Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801

[4] Assistant Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801

Introduction

In regions where seismic hazard is characterized by high-magnitude and infrequent seismic events (for example, the New Madrid seismic zone in the United States), the absence of a recent characteristic seismic event has resulted in a lack of political urgency to support the use of typical seismic resisting structural systems, and a lack of complete knowledge among the local practicing bridge engineering community to address seismic design considerations. These difficulties may result in bridges that are over-designed and do not take full advantage of available mechanisms of seismic isolation, or that are under-designed and do not provide an appropriate margin of safety for earthquake scenarios. To meet these challenges, research is being conducted by the Illinois Center for Transportation (ICT), in collaboration with the Illinois Department of Transportation (IDOT), to refine the existing Earthquake Resisting System (ERS) design methodology so that it is consistent with the nature of the local characteristic seismic hazard. The core of the proposed ERS (Tobias et al. 2008) is an extension of a common bridge design methodology employed in high seismic regions of the United States, where the substructure and superstructure should remain elastic while a fusing mechanism is implemented at the interface between the two (AASHTO 2000, AASHTO 2009). In the context of the IDOT ERS and this research project, the term *fuse* refers to a structural element or assembly that has been designed to provide capacity protection for the rest of the structure by reaching its limit state at a selected level of force. The central objective of the ongoing research is to study the progression of damage in common bridge bearing configurations when subjected to large seismic motions, and the concomitant quasi-isolated response of the global bridge system as various components transition from elastic behavior to alternate forms of response, such as softening and stiffening behaviors in elastomeric materials, post-yield deformation and fracture in steel components, and sliding at selected surfaces.

Experiments will be conducted to investigate the longitudinal and transverse response of three bearing types to seismic demands. The first bearings of interest are the IDOT Type I, 7-c (7 in. x 12 in. plan area) and IDOT Type I, 13-c (13 in. x 20 in. plan area), which are fabricated using an elastomer reinforced with steel shims. Figs. 1(a) and 1(b) show the longitudinal and transverse layout for IDOT Type I, 13-c bearings. These bearings have a direct rubber-to-concrete interface, allowing for the possibility of sliding during an earthquake, and they also include a pair of retainers in the transverse direction. The retainer assemblies, comprised of stiffened L-shaped brackets attached to the concrete substructure with steel anchorage, are designed as fuse components intended to fracture the anchor bolt during a seismic event. The second bearing type of interest is the IDOT Type II, 7-c (7 in. x 12 in. plan area), where the elastomer is joined to steel plates at its bottom and top surfaces through vulcanization. The bottom steel plate of the bearing is bolted to the bridge substructure and the top plate is coated with a layer of polytetrafluoroethylene (PTFE), commonly known as Teflon. Fig. 1(c) shows a view of this bearing system in the longitudinal test layout. An additional steel plate attached to the bridge girder bears on top of the PTFE surface through a thin stainless steel shim welded to the underside of the plate, and this interface facilitates sliding of the superstructure system. Finally, the seismic behavior of fixed bearings, shown tested in the longitudinal direction in Fig. 1(d), is also of interest for this project. The fixed bearing anchor bolts and pintles that prevent movement during ordinary service operations are designed to fail at higher than service loads, thus acting as a fuse mechanism during an earthquake.

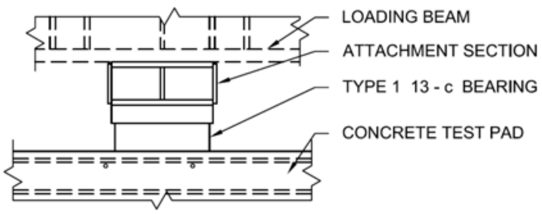


Figure 1(a) IDOT Type I, 13-c longitudinal

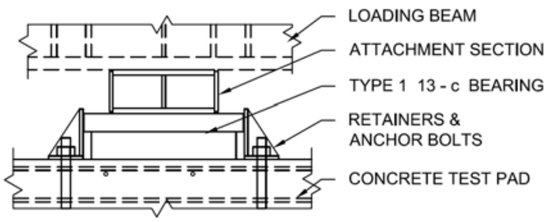


Figure 1(b) IDOT Type I, 13-c transverse

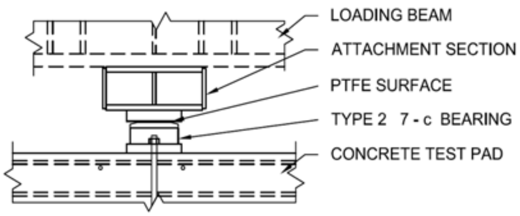


Figure 1(c) IDOT Type II, 7-c longitudinal

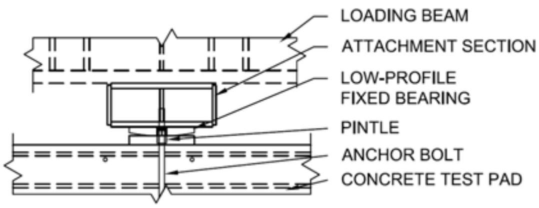


Figure 1(d) Low-profile fixed longitudinal

The purpose of this research is to characterize the fundamental cyclic behavior of full-size bearing assemblies and their associated ancillary components. For IDOT Type I bearings, the elastomer shear response is particularly of interest as it relates to elastomer stiffening and cyclic loading behavior (Kulak and Hughes 1992). Additionally, the friction response between the rubber bearings and the concrete substructure is of interest, as this characteristic establishes a sliding threshold (and the literature contains few representative studies addressing this topic) (McDonald et al. 2000). If, on the other hand, slipping does not occur, then the bearing could experience issues with stability at high elastomer strains (Buckle et al. 2002). In addition to elastomer shear response, a major issue to be studied for IDOT Type II bearings is the sliding at the PTFE surface. Previous research has shown that such sliding behavior is highly dependent on velocity, as well as on applied normal compressive stress (Constantinou et al. 1990).

Typical material specifications and construction practices in Illinois focus on bearing assemblies that are designed primarily for service loads corresponding to relatively small shear displacements, with their seismic response characteristics much less well understood. Furthermore, the other studies mentioned above focus mainly on individual influences for bearing behavior. The current experimental study will incorporate realistic combinations of the various bearing behavior influences for full-size bearings, and provide insight into the degree to which these various aspects affect the overall mechanistic response, thus allowing designers to better utilize the bearings as part of a quasi-isolated ERS methodology.

Experimental Evaluation of Bearings

The bearing tests will be conducted in the Newmark Structural Engineering Laboratory (NSEL) at the University of Illinois at Urbana-Champaign. Two 100 kip actuators, which are attached to a steel reaction frame that is anchored to the strong floor, will be used to apply a vertical load simulating the bearing dead load from a bridge. A 220 kip actuator, which is attached to concrete abutments that are anchored to the strong floor, will be used to apply a horizontal load on a loading beam attached to the bearing specimen, and thus to simulate seismic loads and displacements. This actuator has a stroke of +/- 15 in. and a maximum velocity approaching 4 in./sec, which will allow the testing apparatus to capture the PTFE friction response when subjected to high strain-rate loading. The loading beam is held in place by bracing with roller bearings, and thus the reaction frame will allow for smooth unidirectional load application onto the bearing during testing. Detailed drawings of the South and West Elevations of the testing frame are provided in Figs. 2 and 3.

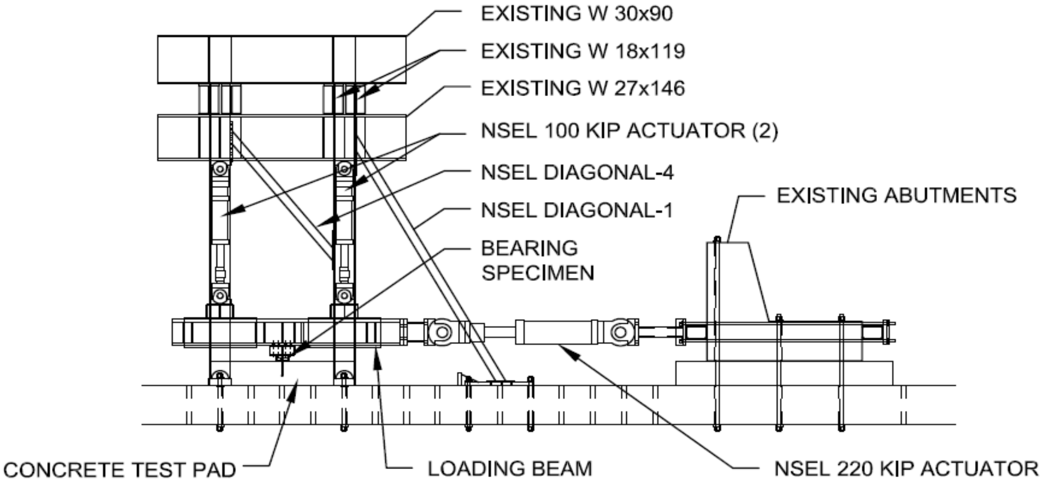


Figure 2. South elevation of test setup

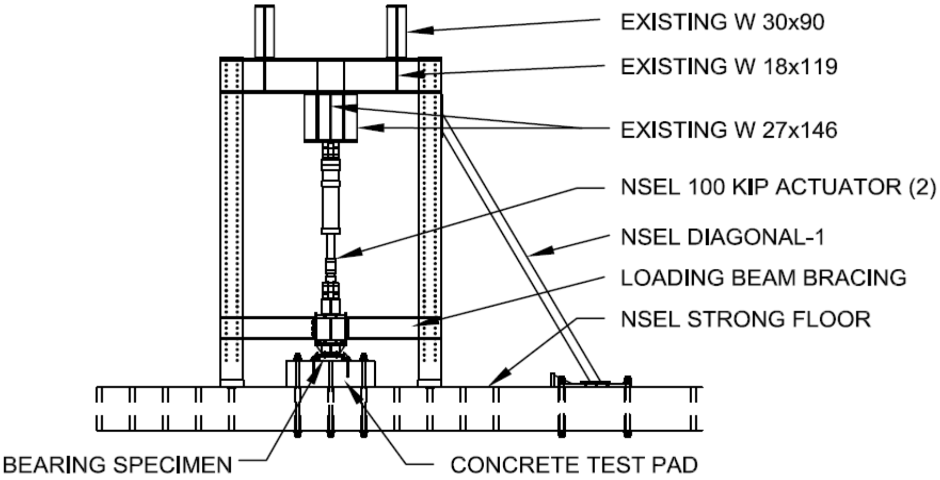


Figure 3. West elevation of test setup

The test matrix is shown in Table 1. The first several tests will investigate bearing response through longitudinal monotonic push testing. Subsequent experiments will include transverse and cyclic tests to completely investigate and characterize the behavior of the system and ancillary components. Displacement demands are characterized by an equivalent strain that reflects the combination of shear deformation in the elastomeric material and also sliding at friction interfaces. Cyclic testing protocols will be based primarily on the AASHTO Guide Specifications for Seismic Isolation Design (AASHTO 2000). In addition to the tests shown, if time and funding permit then further hybrid testing and alternate bearing configurations will be considered. To simulate the behavior of a bridge superstructure on the bearing specimen, a mixed-mode control system will be implemented to maintain loading beam rotation at approximately level and also control shear displacement in the bearing based on the testing protocol in the displacement domain, while holding the simulated gravity load constant throughout a test (in the load domain).

Table 1. Experimental testing matrix

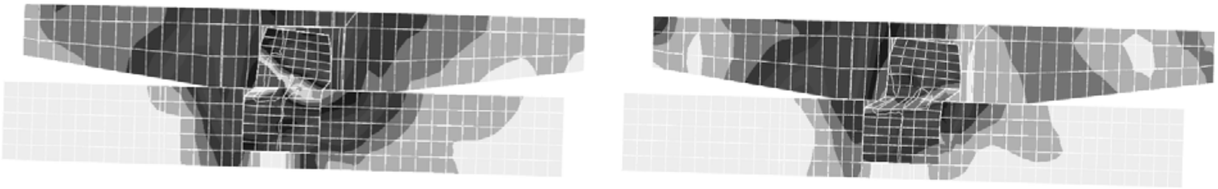
Parameters		**Fixed**	**IDOT Type I**	**IDOT Type II**	**Side Retainers**
Monotonic to Failure	Monotonic				Small
					Large
Cyclic to Failure	Quasi-Static Cyclic: Low Strain Rate				Small
					Large
500 psi, Monotonic to 400% Equivalent Strain	Monotonic		Longitudinal 7-c (three repetitions)	Longitudinal 7-c	
500 psi, Cyclic to 400% Equivalent Strain	Quasi-Static Cyclic: Low Strain Rate	Longitudinal pintle controls	Longitudinal 7-c		
		Longitudinal anchor bolt controls	Transverse 7-c		
		Transverse pintle controls			
		Transverse anchor bolt controls			
	Cyclic: High Strain Rate			Longitudinal 7-c	
				Transverse 7-c	
200 psi, Cyclic to 400% Equivalent Strain	Quasi-Static Cyclic: Low Strain Rate		Longitudinal 7-c		
385 psi, Cyclic to Maximum Actuator Capacity	Quasi-Static Cyclic: Low Strain Rate		Longitudinal 13-c		
			Transverse 13-c		
Hybrid Simulation	Quasi-Static Cyclic: Low Strain Rate		Longitudinal 7-c		
	Cyclic: High Strain Rate		Transverse 7-c		

Bearing Component Analyses

To better understand the bearing components, several preliminary models have been created using Abaqus (Abaqus FEA 2007). The models include material and geometric nonlinearity, as well as contact interactions between elements ranging from hard contact with friction-slip behavior to mechanical or chemical perfect bond. Damage evolution models available in Abaqus/Explicit have also been included to define ranges of material strength degradation, and in so doing to mimic the global effect of crack formation and material fracture.

Steel elements were modeled with an elastic-plastic hardening effect, and subsequent softening was modeled using damage evolution (i.e., due to tension and/or shear fracture). The Abaqus models capture the behavior of concrete subjected to both compressive crushing and tension cracking as a result of force interactions with the embedded anchor bolts, as well as an epoxy layer at the interface of the embedded steel anchor and concrete. A piecewise linear approximation of the Popovics pre- and post-peak compression and the Collins-Mitchell tension stiffening models were used to simulate concrete behavior. An elastomer material model that includes hyperelastic behavior as defined by Yeoh (1993) and that also incorporates damage (scragging) modeled with the Mullins effect (Ogden and Roxburgh, 1998; Abaqus FEA 2007) is currently being implemented. Initial analyses for this study have employed model parameters for elastomeric material based on Stanton et al. (2008), but scaled to adjust for a variation in initial material stiffness.

Fig. 4 below shows a visualization of the von Mises stress contours obtained from preliminary Abaqus analyses of the low-profile fixed bearings. The simulation employs three distinct components: top plate, pintle, and bottom plate. The top plate was moved laterally in displacement control. Hard contact with friction is modeled at all interfaces, and a damage evolution model was used to represent material rupture behavior in the pintle. Note that in Fig. 4(a) a large amount of shear is carried from the top plate through the pintle and into the bottom plate, whereas in Fig. 4(b) the pintle elements have degraded and shear is transferred primarily through friction between the two plates. Ongoing work will investigate the elastomer shear response, the retainer response when subjected to pushover, and also the sliding experienced at elastomer-concrete and PTFE-stainless steel interfaces of IDOT Types I and II bearings, respectively.



(a) Incipient pintle shear failure

(b) After shear failure

Figure 4. Shear failure at low-profile fixed bearing

Bridge System Model Analyses & Seismic Design Methodology

The experimental testing along with detailed Abaqus component modeling illuminates key mechanisms for the behavior of both the bearings and their ancillary components. Those results are being incorporated into full system models that are analyzed using the open source, nonlinear seismic analysis program Open System for Earthquake Engineering Simulation (OpenSees 2006). Leveraging the malleability of the open source code to directly incorporate user-defined elements and material models, this project is implementing modeling features that appropriately reflect the progression of damage throughout a bridge system based on data garnered from the experiments. Thus, the system models can accurately incorporate the bearing behavior and provide insight into the behavior of the complete bridge structure.

The system analyses are being carried out as a sensitivity study that investigates several aspects of bridge design and behavior. As a primary step, a base bridge model was created that has three spans and allows for two lanes of traffic. This base bridge model is being modified as shown in Table 2, such that the main parameters will be explored through the computational study. The primary focus is on investigating the interdependency of the bearings with the super- and sub-structure response, followed by development of design recommendations to appropriately account for seismic quasi-isolation with respect to force and displacement demands.

The initial base bridge model has a superstructure composed of steel girders and an 8 in. concrete deck. There are three 50 ft spans, and the intermediate substructures are 15 ft tall multi-column piers. A preliminary bilinear kinematic material model was used to simulate IDOT Type I elastomeric bearings at both abutments and at the left pier. A fixed bearing was assumed at the right pier. The base bridge model behavior was simulated using a synthetic earthquake record with a 2500-yr return period, generated for Paducah, KY (Rix and Fernandez 2006), where the seismic hazard is dominated by large magnitude, but infrequent, seismic events in the New Madrid seismic zone. Fig. 5 shows the preliminary bridge model with 50 times magnified deflections on the bridge when subjected to an earthquake in the longitudinal direction.

Table 2. System analysis matrix

		Bridge Type 1 Steel - Short				Bridge Type 2 Steel - Long				Bridge Type 3 Concrete - Short				Variations
Parameter	Alternatives	1	2	3	4	5	6	7	8	9	10	11	12	
Span Length & Bridge Type (ft)	50' - 50' - 50'	*	*	*	*									3
	60' - 60' - 60'									*	*	*	*	
	80' - 120' - 80'					*	*	*	*					
Intermediate Sub-Structure	Continuous Wall	*	*			*	*			*	*			2
	Multi Column Pier			*	*			*	*			*	*	
Intermediate Sub-Structure Height	Short - 15'	*		*		*		*		*		*		2
	Tall - 40'		*		*		*		*		*		*	
Movement Bearings	Type 1 Elastomeric	All (12) of the above bridges will be modeled with Elastomeric Type 1 & Type 2 Bearings												2
	Type 2 Elastomeric													

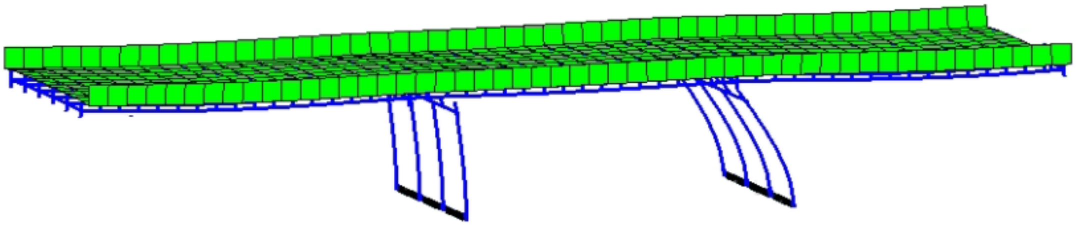


Figure 5. Preliminary system model created using OpenSees

The preliminary bridge model experienced a maximum deck displacement of 4.9 in. when subjected to the earthquake record, when no backwall effects were simulated and no fusing behavior was modeled at the fixed bearing. Fig. 6 shows the displacement history for this analysis. For this case, the IDOT Type I, 7-c elastomeric bearings located at the abutments experience up to 267% equivalent shear strain, assuming no slip at the concrete surface. This preliminary model is being refined to integrate additional characteristics, such as impact at backwalls, fusing at the fixed bearing, and a frictional stick-slip response for elastomer-on-concrete behavior at IDOT Type I bearings.

Fig. 7(a) shows a displacement history where the longitudinal displacement in the bridge is limited by the abutment backwall, which was placed with a gap of 2 in., as it would be in a typical bridge to allow for thermal expansion. Fig. 7(b) shows the spikes of impact force experienced by the backwall when the deck displacement exceeded 2 in. Currently the backwall is modeled as a very stiff gap element with a linear response in compression, but more realistic behavior will be incorporated into the bridge model when soil and foundation analyses have been completed. A material model simulating the frictional stick-slip behavior at a single bearing subjected to an earthquake motion is shown in Fig. 8; in this case, slip initiates at 30 kips of shear, and subsequent sliding friction results in a 40% decrease of shear transmitted at the slip surface.

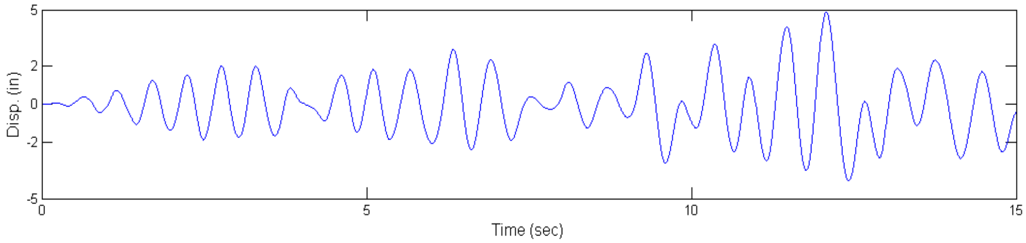


Figure 6. Displacement vs. time, experienced by bridge deck (no backwall)

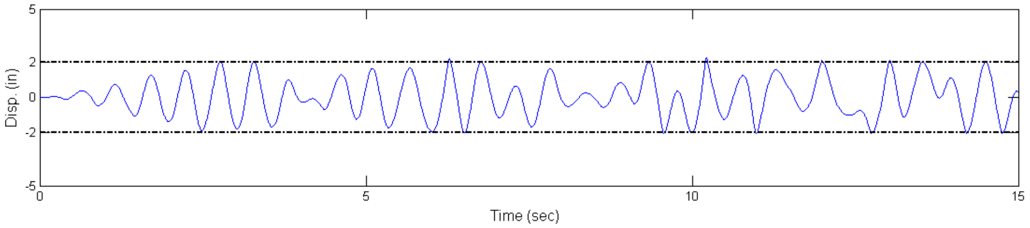


Figure 7. (a) Displacement vs. time, experienced by bridge deck (with backwall)

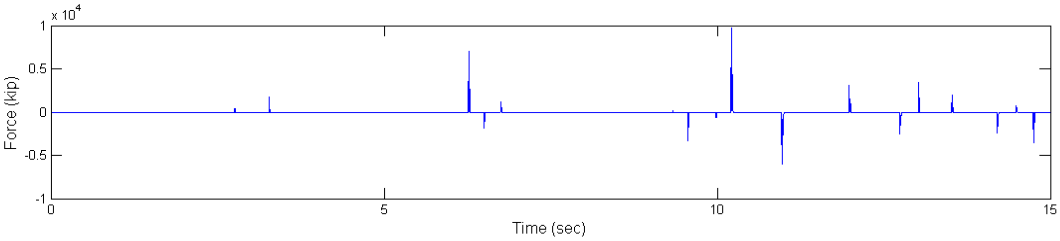


Figure 7. (b) Impact force vs. time, experienced by backwall

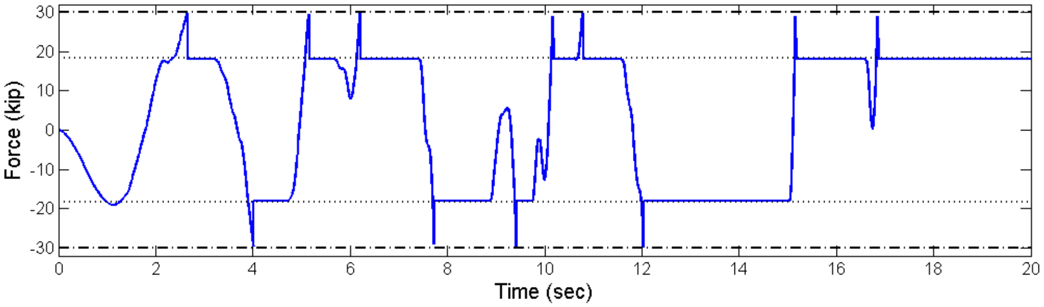


Figure 8. Shear force vs. time due to friction at bottom of elastomeric bearing

Summary and Conclusions

The ultimate objective of this research is to develop refined design recommendations for seismic engineering of bridges subjected to infrequent but potentially large-magnitude earthquakes, as may be experienced in mid-America, based on the system analyses and experimental results for bridge systems that are common in the region. These recommendations will improve and suggest calibration for design requirements already in use, and will also include proposed modifications or additional design guidelines where appropriate (for example, seismic response factors and complementary nonlinear analysis procedures). The primary concerns for a quasi-isolated system being addressed in this study are a more exacting quantification of ultimate capacities for selected fuse components and determination of displacement demands for an effectively isolated superstructure. This paper summarizes computational results to date, including both detailed three-dimensional nonlinear analyses of bearing assemblies and nonlinear dynamic analyses of complete bridge systems that model the effects of elastomer shear, sliding, fixed bearing pintle yield and fracture, and impact of the bridge colliding with an abutment backwall. Future research includes a complete set of experimental tests and a sensitivity study of the bridge systems.

Acknowledgments

This article is based on results from ICT R27-70, *Calibration and Refinement of Illinois' Earthquake Resisting System Bridge Design Methodology*. ICT R27-70 is being conducted in cooperation with the Illinois Center for Transportation (ICT); Illinois Department of Transportation (IDOT), Division of Highways; and the U.S. Department of Transportation, Federal Highway Administration (FHWA). The contents of this article reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the ICT, IDOT, or FHWA. The authors would like to thank the members of the project Technical Review Panel, especially Panel Chair and IDOT Structural Development Engineer D. H. Tobias, for their assistance with this ongoing research.

References

Abaqus FEA, 2007. SIMULIA website, Dassault Systèmes, Vélizy-Villacoublay, France. http://www.simulia.com/products/abaqus_fea.html

American Association of State Highway and Transportation Officials (AASHTO), 2000. *Guide specifications for seismic isolation design with interims*, Washington, D.C.

AASHTO, 2009. *Guide specifications for LRFD seismic bridge design*, Washington, D.C.

Buckle, I., S. Nagarajaiah, and K. Ferrell, 2002. Stability of Elastomeric Isolation Bearings: Experimental Study, *Journal of Structural Engineering* 128, (1), 3-11.

Constantinou, M. C., A. Mokha, and A. M. Reinhorn, 1990. Teflon Bearings in Base Isolation II: Modeling, *Journal of Structural Engineering* 116, (2), 455–474.

Kulak, R. F. and T. H Hughes, 1992. Mechanical Tests for Validation of Seismic Isolation Elastomer Constitutive Models, *DOE Facilities Programs, Systems Interaction, and Active/Inactive Damping, Eds. C.-W. Lin et al., ASME Publication PVP* 229, 41-46.

McDonald, J., E. Heymsfield, and R. R. Avent, 2000. Slippage of Neoprene Bridge Bearings. *Journal of Bridge Engineering* 5, (3), 216-223.

Ogden, R. W. and D. G. Roxburgh, 1998. A Pseudo-Elastic Model for the Mullins Effect in Filled Rubber. *Mathematical, Physical and Engineering Sciences 455,*(1988), 2861-2877.

OpenSees, 2006. OpenSees website, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA. http://opensees.berkeley.edu/OpenSees/home/about.php

Rix, G. J. and J. A. Fernandez, 2006. Probabilistic ground motions for selected cities in the Upper Mississippi Embayment. Georgia Institute of Technology, Atlanta, http://www.ce.gatech.edu/~geosys/soil_dynamics/research/groundmotionsembay/

Stanton, J. F., C. W. Roeder, P. Mackenzie-Helnwein, C. White, C. Kuester, and B. Craig, 2008. Rotation Limits for Elastomeric Bearings. *National Cooperative Highway Research Program* 596. Washington, D.C: Transportation Research Board.

Tobias, D. H., R. E. Anderson, C. E. Hodel, W. M. Kramer, R. M. Wahab, and R.J. Chaput, 2008. Overview of Earthquake Resisting System Design and Retrofit Strategy for Bridges in Illinois. *Practice Periodical on Structural Design and Construction* 13, (3), 147-158.

Yeoh, O. H., 1993. Some Forms of the Strain Energy Function for Rubber, *Rubber Chemistry and Technology* 66, (5), 754–771.