Implementation of Lock-Up Guides for Segmental Displacement Control Design of Seismically Isolated Bridges

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SUMMARY:
Non-structural components are often overlooked in the seismic design of bridges, thereby establishing a threat to the post-earthquake functionality of a structure and the surrounding economic region. For multi-segment isolated bridge systems, the innovative concept of Segmental Displacement Control (SDC) design is increasingly used to constrain the relative movement of the individual isolated bridge segments in such a way that the bridge's centerline remains continuous without significant transient or residual offsets. The continuity of SDC design minimizes damage to expansion joints, utilities, or other components continuing between segments, where economical one-dimensional expansion joints can be used, rather than more complex multi-directional joints. This behavior can be achieved using special lock-up guides, concave triple friction pendulum isolation bearings, and concave single friction pendulum isolation bearings. Experimental shake table tests validate the effectiveness of SDC design largely through the reduction of transverse relative displacements between adjacent bridge segments, thereby providing a new and safer system for seismically isolated bridges.

Keywords: Segmental displacement control design, lock-up guide, seismic bridge isolation, friction pendulum

1. INTRODUCTION

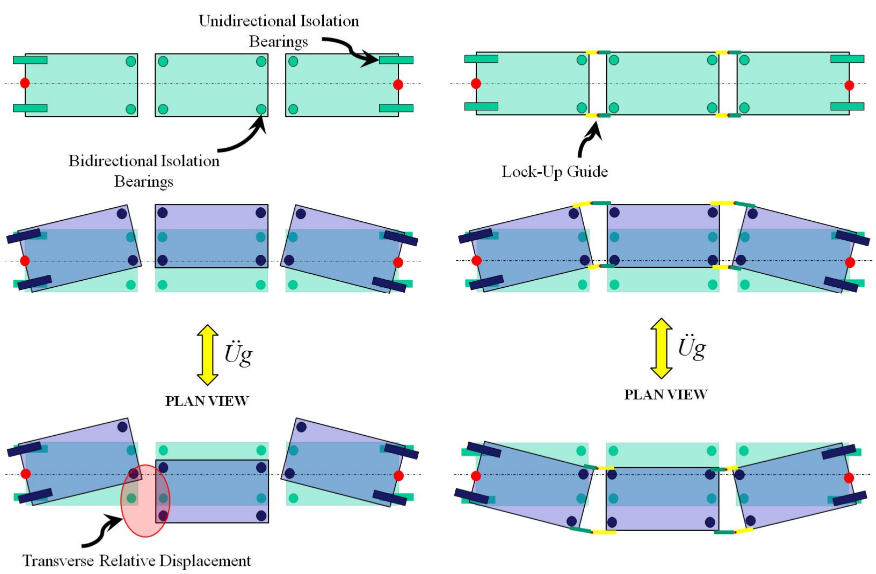
Applicable to both new and retrofit design, seismic isolation is traditionally implemented in structural engineering to mitigate earthquake hazards by decoupling the superstructure from the horizontal components of ground excitation. This is accomplished by installing a flexible isolation layer directly underneath the superstructure that absorbs a majority of the energy, particularly high frequency, present in a seismic event. The overall benefits of an isolated structure are mitigated force demand on the foundation and reduction in the accelerations propagated throughout the superstructure. The latter is advantageous for preserving the non-structural components within the superstructure, thereby emphasizing a more resilient structural system through continued functionality during a major seismic event. Currently and in general, neither bridge codes nor bridge specifications directly address the issue of system functionality through preserving the non-structural components of a structure. This is an extremely important issue for bridges because they serve as lifelines within an economic region. Therefore, future design methodologies must accommodate life safety as an objective, as well as shifting attention to the importance of a structures' functionality after a major seismic event. Thus, controlling the amount of relative displacements between adjacent bridge decks in order to preserve non-structural components is the topic of interest for this paper. SDC design has been referenced by Mahin et al. (2011). However, a general recap of SDC concepts and the technical results of a portion of the experimental program within Mahin et al. (2011) are presented hereafter. Emphasis is drawn to the behaviour of the lock-up guides within SDC design concept, as well as to the performance of the friction pendulum isolation bearings, all provided by Earthquake Protection Systems (EPS).

2. SEGMENTAL DISPLACEMENT CONTROL DESIGN

An isolated bridge will inherently develop large relative displacements between adjacent bridge decks because of spatial variations among bridge bent and abutment responses, and geometric irregularities. Countermeasures to attenuate out of phase response, depending on the type of isolation bearings used, for example are proportioning isolation bearing properties, superstructure mass, or using supplemental devices. The latter is used within the concept of SDC design, which is developed by EPS, to minimize seismic damage of non-structural components within long-span bridges in an attempt to preserve system functionality after a major seismic event.

2.1. Concept

The underlying principles of SDC design emphasize the reduction of relative transverse displacement between adjacent bridge decks to preserve the non-structural bridge components, such as utilities, rails, and expansion joints. This is presented in Fig. 2.1, where the fundamental transverse behaviour of an isolated bridge with three bridge decks is displayed in plan view. The center bridge deck is fully supported by bearings that allow longitudinal and transverse coupled displacement, shown as circles. However, the end bridge decks are restrained in the transverse direction at the extreme ends shown as rectangles, characterizing a typical configuration for a highway or railway bridge. Only three bridge decks are displayed in the conceptual figure. A real-life bridge would typically have more decks in series that are fully supported by bearings with longitudinal and transverse freedom. Fig. 2.1 (a) shows unrestrained bridge decks, thus leading to large transverse relative displacements. Whereas, Fig. 2.1 (b) displays a pair of lock-up guides between two adjacent bridge decks, thereby mitigating the relative transverse displacement between bridge decks and defining the mode shapes for the superstructure. These overall mode shapes are characteristic of longer periods and therefore produce lower forces at the hinged connections.



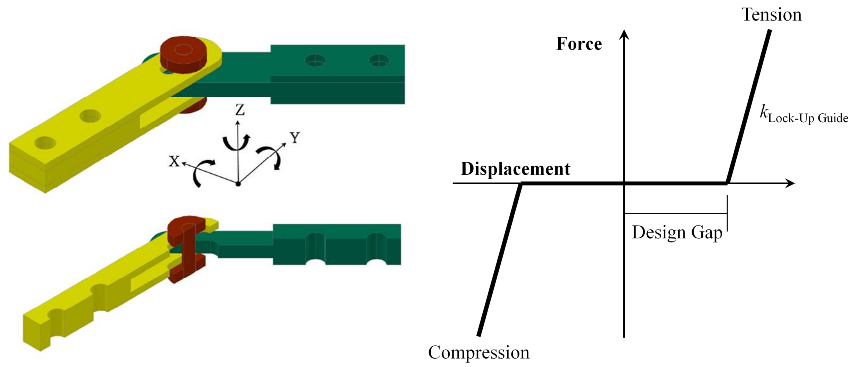
(a) Unrestrained bridge decks (b) Restrained bridge decks

Figure 2.1. Segmental displacement control design concept plan view

2.2. Lock-Up Guide

To improve performance within isolated bridge systems, various devices and methodologies have been studied. Established in Japan by the Public Works Research Institute et al. (1992), the Manual for Menshin Design of Highway Bridges was a notable attempt to concentrate efforts to develop compatible energy dissipation devices, fall-off prevention devices, expansion joints, and rational design methods. Controlling of relative displacements between bridge decks has been further researched throughout Europe, Japan, and the United States, where notable recommendations for design of hinge restrainers are provided through Priestley et al. (1996) and DesRoches et al. (1997). Examples of supplemental devices are steel cables, various types of dampers, and shock absorbers. However, in general, past studies and restraining devices are focused to the longitudinal direction and do not emphasize minimizing the transverse relative displacement for preserving the non-structural components throughout entirety of the bridge system. Infanti et al. (2004) provides a real-life example of the Rion-Antirion Bridge, Greece, where elastomeric bearings were used for superstructure isolation and nonlinear fluid viscous dampers were independently oriented in the longitudinal and transverse directions to minimize relative displacements.

The following sketch visualizes the restraining device proposed by EPS along with its theoretical force-displacement relationship in the longitudinal direction. The restraining device contains three steel plates, or fingers, that overlap each other and are joined through a slotted-pin connection. The slot has a displacement capacity that is user-defined according to thermal considerations and the performance of the bridge system in the longitudinal direction, for instance the different requirements of highway, freight railway, and high-speed railway bridges. Thermal expansion is allowed, yet for a major seismic event, the pin will “lock up” in the slot upon exceeding displacement capacity. Transverse displacement is restricted by the stiffness of the pin and the surrounding fingers strength of the lock-up guide. Thus, the lock-up guide provides a simple supplemental device for isolated bridges that is low cost, requires minimal maintenance, can be used as a sacrificial element, and most importantly can accommodate a prescribed amount of longitudinal relative displacements while attenuating the transverse relative displacements.



(a) Isometric AutoCAD sketch-up (b) Theoretical longitudinal force-disp. relationship

Figure 2.2. Lock-up guide

3. EXPERIMENTAL TESTS

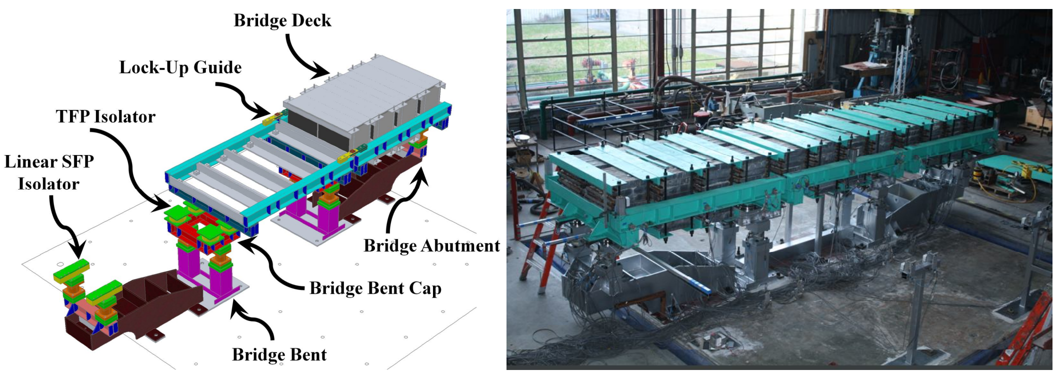
To validate the effectiveness of SDC design for isolated bridges, an experimental program was designed to implement a series of sinusoidal and seismic excitations on a shake table to a scaled isolated bridge, where a direct comparison between an isolated bridge and an isolated bridge with installed lock-up guides was studied. Particular emphasis was placed on the behavior of the concave friction pendulum isolation bearings.

3.1. Testing Facilities

All excitation tests were conducted on the shake table at the Pacific Earthquake Engineering Research (PEER) Center at the University of California, Berkeley. This facility houses a 6 DOF shake table in the United States that measures 20 ft by 20 ft. A total of twelve hydraulic actuators provide quoted limitations of plus and minus 5 inches of horizontal displacement, 2 inches of vertical displacement, 3 g’s of horizontal and vertical acceleration, and 140 kips of vertical payload.

3.2. Test Specimen

A quarter-scale steel bridge specimen was constructed to validate SDC concepts. To preserve acceleration similitude, a length scale of 4 and a time scale of 2 were implemented. Fig. 3.1 shows a dissected sketch and the experimental specimen of the isolated bridge. A total of three bridge decks comprise the bridge with the same notion represented in Fig. 2.1. The end bridge decks were isolated with four concave single friction pendulum (SFP) bearings at the deck ends, which were restricted in the transverse direction, representing the west and east abutments. In addition, eight concave triple friction pendulum (TFP) bearings were located on top of the bent caps at the interior bents. Thus, the center bridge deck is isolated with only TFP isolation bearings. Each bridge bent consisted of a single bent cap and two columns. All superstructure and substructure components adhered to an elastic AISC capacity design. Each bridge deck contained 30 kips of lead weight.



(a) Dissected AutoCAD sketch-up (b) Experimental specimen on shake table

Figure 3.1. Quarter-Scale Isolated Bridge

3.2.1. Friction Pendulum Isolation Bearings

The concept behind isolation bearings involving friction undertook the basics of a pendulum mechanism system developed by Zayas et. al. (1987) at the University of California, Berkeley. Within the past decade, numerous publications have studied the SFP, the double concave friction pendulum, and the TFP bearings. As seen in the following figures, the isolation bearings at the experimental bridge abutments were concave SFP behavior in the longitudinal direction and restricted in the transverse direction through three independently connected components from bottom to top, respectively: housing, slider, and rail.

(a) All components (b) Housing (c) Orientation and tolerances

Figure 3.2. Experimental concave SFP isolation bearing

Connected to the bent side of the end bridge decks and the center bridge deck, concave TFP bearings were used for bi-directional isolation response. Fig. 3.3 presents experimentally installed and a cross-sectional view of the five components comprising the TFP bearing. Dependent on radii of curvatures, effective pendulum lengths, and the diameters and heights of the inner slider, inner concave dishes, and outer concave dishes, Table 3.1 highlights properties for the experimentally-scaled and prototype bearings.

(a) Experimentally Installed (b) Cross section component sketch-up (EPS)

Figure 3.3. Experimental concave TFP isolation bearing

Table 3.1. General friction pendulum isolation bearing properties

Isolation Bearing	Measurement	Scaled[a,b]	Prototype[a,b]
SFP	Max Disp.	8.75	35.00
	Stage I Period	2.00	4.00
TFP	Max Disp.	6.52	26.08
	Stage I Period	0.71	1.42
	Stage II Period	1.43	2.86
	Stage III Period	1.90	3.80
	Stage IV Period	1.43	2.86
	Stage V Period	0.71	1.42

[a] Displacement = inches and Period = seconds

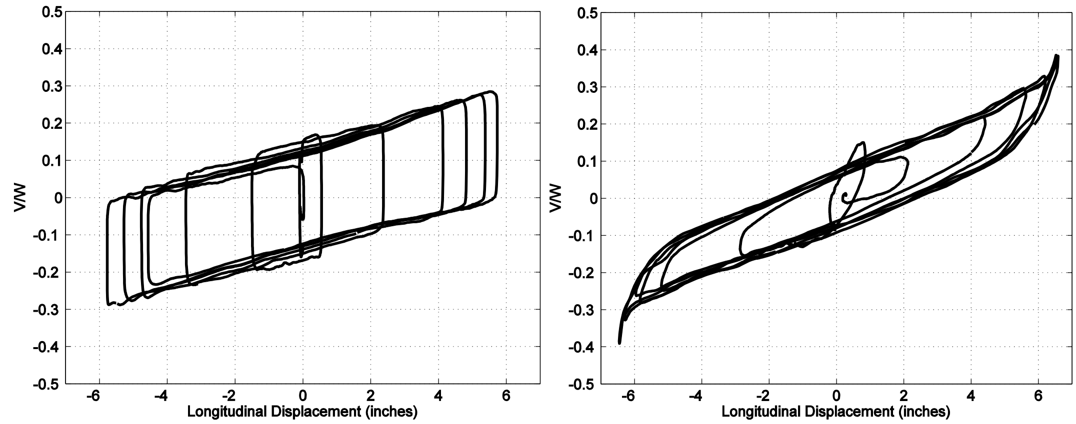
[b] Similitude requirement: Length/(Time)^2 = 4/(2)^2=1

3.2.2. Lock-Up Guide

The lock-up guides were designed to remain elastic to the expected forces at maximum isolator displacements, where member sizes were proportioned by free body diagrams similar to methods by Priestley et al. (1996). The lock-up guide slot length is in general user defined for a specific relative displacement requirement. However, the lock-up guide slot length should not impede on bearing functionality. Therefore, the experimental slot length was minimally designed to the longitudinal displacement of the TFP isolation bearing on the end deck at maximum end deck rotation. Referencing Fig. 2.2 (b), the primary lock-up guide, Lock-Up Guide Set#2, is symmetric in behavior and contained a tension and compression displacement capacity of 2.5 inches. For study of bridge response while maximizing the slot length displacement capacity, Section 4.2, the lock-up guide was modified to 1.25 and 2.5 inch compression and tension displacement capacities, respectively. Reference to this behavior is addressed as Lock-Up Guide Set#1. The specific design and optimization of lock-up guide properties may be found in Ogorzalek et al. (2012).

3.3. Characterization Tests

To obtain isolation bearing properties and validate free body mechanics of the isolated bridge system, sinusoidal cyclic tests were conducted in the transverse and longitudinal directions. Fig. 3.4 displays the hysteric behaviour for all isolation bearings in the longitudinal direction, where V/W equates to shear force normalized with axial force. From these plots, the friction coefficients are determined following the methods of Morgan (2008). The friction coefficient measured for the SFP isolation bearing is 12%. For the TFP isolation bearings, the three friction coefficients are approximated as 5%, 8%, and 13%, where the shear and axial forces for a single bent are averaged between two load cells. Therefore, TFP hysteresis is not a direct one to one relationship between individual isolation bearing and the load cell, as opposed to the SFP isolation bearings.



(a) SFP (b) Center deck TFP

Figure 3.4. Normalized force displacement hysteresis of isolation bearings

3.4. Earthquake Motions

After completion of characterization tests, a series of ground excitations were used for SDC concepts based on source mechanism, site conditions, and accessibility, Table 3.2. Each excitation was scaled to a target absolute displacement of 2.0, 3.4, and 5.0 inches for the end deck TFP bearings, thereby respectively corresponding to the service level earthquake (SLE), design basis earthquake (DBE), and maximum considered earthquake (MCE). These performance objectives translate to approximately 50% in 50 years, 10% in 50 years, and 2% in 50 years probabilities of exceedence, respectively.

Table 3.2. Experimental selection of ground excitations

Source	Source ID	Record
SAC Ground Motion	NF01/NF02/NF0102v	1978 Tabas, Iran
PEER Strong Motion	SYL090/SYL360/SYL-UP	Sylmar, 1994 Northridge, USA
	KJM000/KJM090/KJM-UP	JMA, 1995 Kobe, Japan

4. EXPERIMENTAL RESULTS

The main priority for SDC design response is to reduce the relative transverse displacements between adjacent bridge decks while also monitoring the overall response of the bridge system, as seen through 130 measurement channels. Transverse and longitudinal relative displacements are measured in the global direction for the two hinge locations within the isolated bridge. Important topics of interest for SDC validation are as follows.

4.1. Effect of Primary Lock-Up Guide

For all ground excitations and hazard levels, Fig. 4.1 presents the range of percent change in response between an isolated bridge with and without installed Lock-Up Guide Set#2. The ratio is the difference between responses with and without lock-up guides divided by the response without lock-up guides installed (+ increase). For displacements, the transverse relative displacements are measured from two locations, where these measurements are shown at the ends of the percent range of change bars. Similarly, four locations are measured for each the longitudinal relative displacements, the linear SFP, the end deck TFP, and the center deck TFP absolute bearing displacements. The average value is distributed among the four measurements for each category. With regards to forces, Fig. 3.1 (a) displays two load cells underneath each bridge abutment and bent. Therefore, measurements from two load cells are combined to provide a single support force for the longitudinal, transverse, and axial directions. Two abutments correspond to two measurements, which are shown at the ends of the percent range of change bar and averaged by a single marker. Fig. 4.1 displays all ranges of percent changes in forces for each direction within the bents and abutments, respectively labelled as Bent F. and Abut. F.

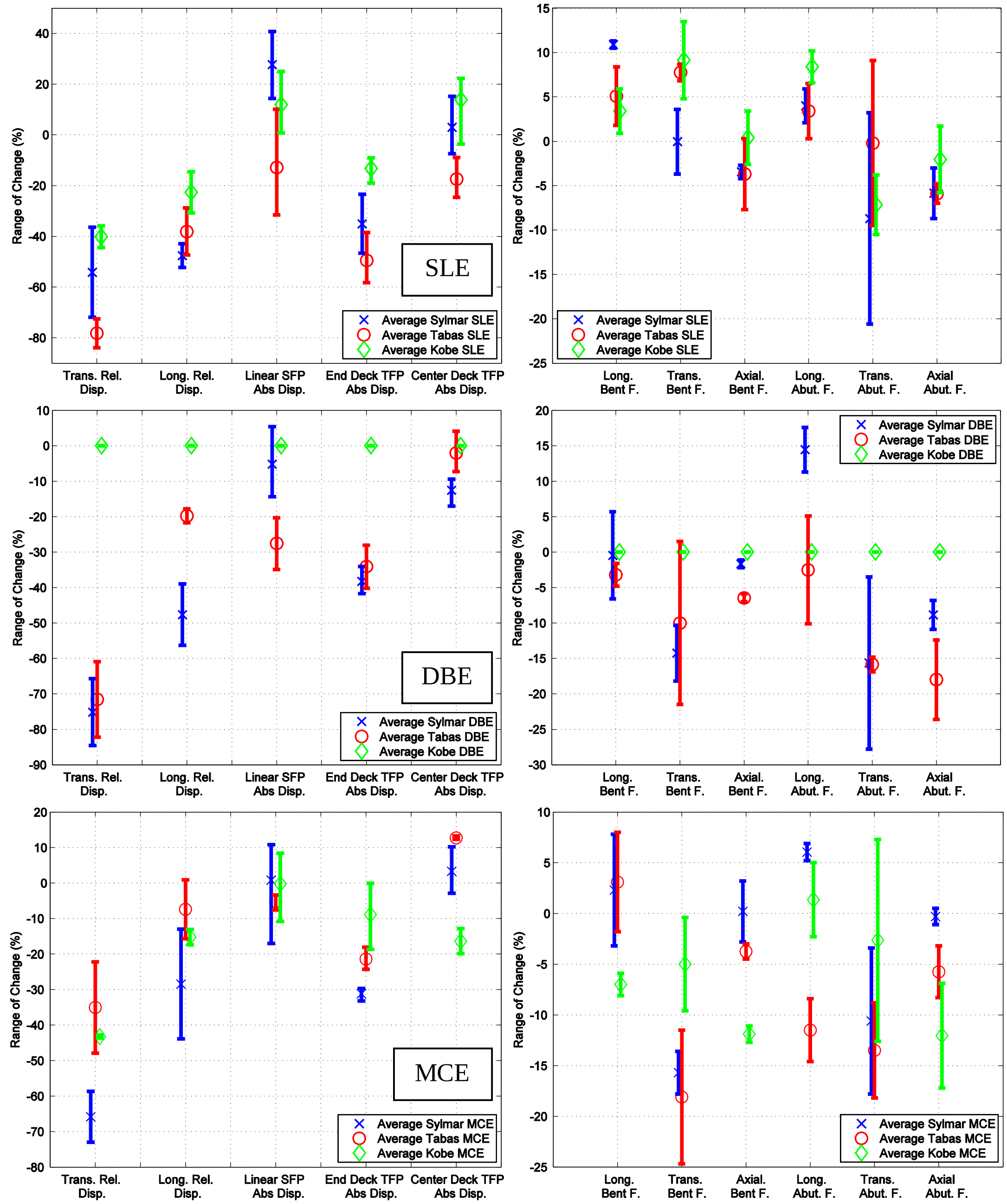
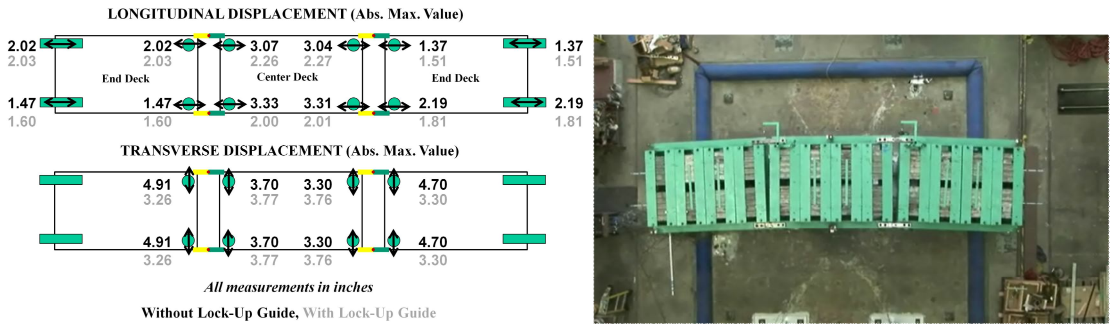


Figure 4.1. Displacement and force comparison between isolated bridge with and without Lock-Up Guide Set#2 at SLE, DBE, and MCE excitation levels

In comparing all excitations and hazard levels, noticeably there is a significant reduction in relative transverse displacement, thereby validating the effectiveness of the lock-up guide to preserve non-structural components. The maximum reduction, 85%, occurred at the DBE level. In addition, general trends show reductions in the longitudinal relative displacements between bridge decks and the end bridge deck TFP bearing absolute displacements. The latter is emphasized in Fig. 4.2 (a) for transverse displacements of the TFP isolation bearings during the Sylmar MCE level excitation, 0.64g PGA. Fig. 4.2 also illustrates first mode response in the transverse direction and overall more unison with the isolation bearing displacements. However, increase or decrease in percent change fluctuates for the linear SFP and center deck TFP bearing displacements.



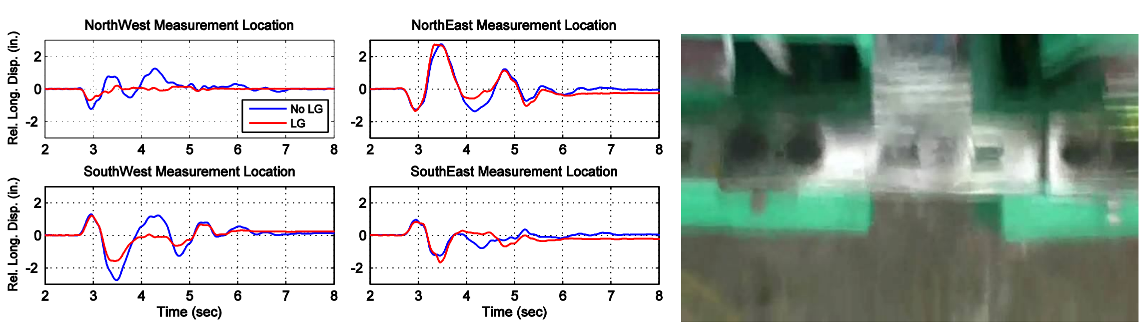
(a) Plan view of isolation bearing displacements (b) Maximum transverse response with lock-up guide

Figure 4.2. Superstructure response with and without Lock-Up Guide Set#2 to Sylmar MCE level excitation

Regarding substructure forces, the reduction in end deck TFP bearing transverse displacements resulted in reduction of transverse and axial forces at the bents and abutments, particularly seen at the DBE and MCE hazard levels. However, fluctuations arise in percent changes for longitudinal forces. For all hazard levels, superstructure displacements are more similar in response for all excitations when compared to the substructure forces. The latter is attributed to unintended flexibility of the end abutments.

4.2. Effect of Maximizing Lock-Up Guide Slot Length

To study the effect of bridge response while maximizing the lock-up guide slot length, Sylmar MCE level excitation was scaled to 0.76g PGA and the bridge was installed with Lock-Up Guide Set#1. Fig. 4.3 (a) compares the relative longitudinal displacements at the bridge expansion joints for experimental tests without (No LG) and with lock-up (LG) guides, which indicates bridge behavior is not fully symmetric and the northeast lock-up guide reaches the 2.5 inch tension displacement capacity at approximately 3.3 to 3.6 seconds. During this interval, there is a 0.37g and a 0.20g increase in longitudinal accelerations on the east and center decks, respectively, as shown in the close-up of Fig. 4.4. However, these acceleration spikes do not exceed the maximum deck accelerations throughout the full time history.



(a) Time histories (b) N.E. lock-up guide max. tension (blurred)

Figure 4.3. Relative longitudinal displacements at expansion joints with and without Lock-Up Guides Set#1 to Sylmar MCE+ level excitation

For response of support forces, Fig. 4.4 shows all locations of load cells, where Table 4.1 highlights the absolute maximum forces between experimental tests without and with lock-up guides during the

3.3 to 3.6 second interval and for the full time history. At lock-up maximum tension, forces fluctuate with small increases or decreases depending on the specific support. However, these forces do not exceed the maximum forces measured throughout the full time history. This indicates that even though maximizing the displacement capacity of the lock-up guide induces spikes in longitudinal accelerations, there is minimal effect translated to the support reactions. Also, impact of maximum slot length did not yield the lock-up guides, as provided by longitudinal strain gauges.

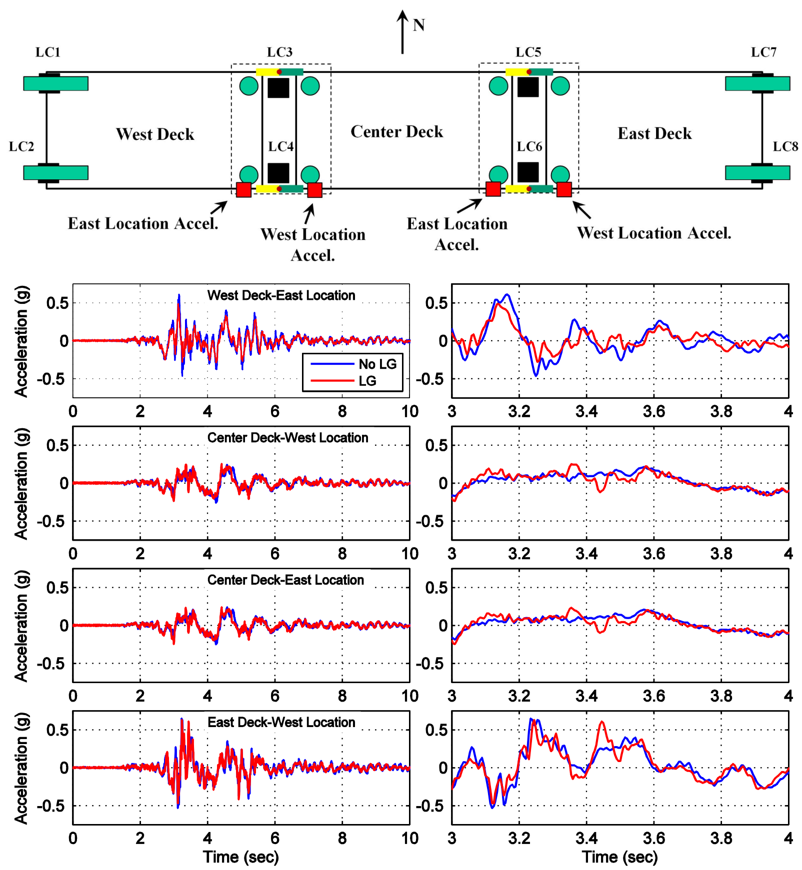


Figure 4.4. Superstructure accelerometer deck locations and time histories

Table 4.1. Comparison of longitudinal shear forces at all bridge supports

Measurement Location	Load Cell Measurement ID	Longitudinal Shear Force[a]			
		At Lock-Up Max. Tension[b]		Full Time History	
		No LG	LG	No LG	LG
West Abutment	LC 1	1.98	2.38	2.79	2.56
	LC 2	1.87	1.96	1.91	1.96
West Bent	LC 3	3.04	2.34	3.22	3.40
	LC 4	2.30	2.84	3.68	3.75
East Bent	LC 5	2.76	1.87	3.84	3.85
	LC 6	2.41	2.30	3.38	3.08
East Abutment	LC 7	1.68	1.63	3.06	2.62
	LC 8	1.57	1.80	2.30	2.71

[a] Shear force = kips, All measurements as absolute maximum

[b] Lock-up interval of interest from 3.3 to 3.6 seconds

5. CONCLUSIONS

An innovative concept for improving resilience of isolated bridges is presented. This concept is known as Segmental Displacement Control, as it highlights preserving non-structural components for immediate functionality of a structure after a major earthquake. After completion of an experimental program, installation of lock-up guides that contain symmetric tension and compression displacement capacities resulted in significant reductions to the transverse relative displacements between adjacent bridge decks. The latter was a direct result of forcing first mode bridge behaviour in the transverse direction, where the transverse displacements of the TFP isolation bearings were similar between bridge decks. In addition, general trends show a reduction in the relative longitudinal displacements of adjacent bridge decks as well as in the end deck TFP isolation bearing transverse displacements, thereby resulting in the reduction of absolute maximum transverse and axial forces at the bridge bents and surprisingly at the bridge abutments. For all support locations, absolute maximum longitudinal forces fluctuate with increasing or decreasing values dependent on the excitation and hazard level. Similar results are representative of the SFP and the center deck TFP isolation bearings.

Studying bridge response to maximizing the lock-up guide slot length, lock-up guides with unsymmetric tension and compression displacement capacities were installed on an isolated bridge subjected to the 1994 Northridge, Sylmar excitation at MCE+ level with 0.76g PGA. Results indicate that at maximum tension and compression slot length capacity, there is a sudden increase in longitudinal acceleration, 0.37g absolute maximum, between the bridge decks nearest to the corresponding lock-up guide. However, impact accelerations do not exceed the maximum accelerations recorded on the bridge decks throughout the full time history. Also, the impact of the finger joints within the lock-up guide does not produce yielding forces, as measured by strain gauges. With respect to substructure forces, there are small fluctuations with increases or decreases, though substructure forces during impact do not exceed the absolute maximum forces measured throughout the full time history.

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