The Influence of Vertical Earthquake Motion and Pre-Earthquake Stress State on the Seismic Response of Precast Segmental Bridge Superstructures

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ABSTRACT

Precast segmental construction methods can ease bridge construction costs by reducing construction time while maintaining quality control. In addition, the absence of falsework can minimize traffic congestion and environmental impact, adding to the benefits of this accelerated bridge construction method. While the popularity of precast segmental bridge construction has increased throughout the world, its use in seismic regions of the United States has been hampered by a lack of research on the seismic response that would lead to reliability in its use. This research investigated the seismic response of precast segmental bridges with bonded tendons constructed with the balanced cantilever construction method, using detailed 2D non-linear time history analyses. A number of models were developed, including a validation model and two simulations of full scale balanced cantilever bridges with span lengths of 300 and 525 feet. These models utilized geometries and characteristics, similar to the Otay River Bridge and the San Francisco-Oakland Bay Bridge Skyway in California and were subjected to a suite of twenty near field earthquake records. This paper will show that the vertical component of ground motion significantly affected the segment joint response and the magnitude of the response can vary dramatically depending on the pre-earthquake stress-state (i.e. the effects of creep, shrinkage and temperature) in the superstructure.

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INTRODUCTION

Precast segmental construction of bridges can accelerate construction and minimize the cost of bridges in highly congested urban environments and environmentally sensitive regions. While the popularity of precast segmental bridge construction has increased throughout the world, its use in seismic regions of the United States has been hampered by a lack of research on the seismic response that would lead to reliability in its use. The California Department of Transportation (Caltrans) supported a research program to address this concern. This research investigated the seismic response of precast segmental bridges with bonded tendons constructed with the balanced cantilever construction method, using detailed 2D non-linear time history analyses. A number of models were developed, including a validation model and two simulations of full scale balanced cantilever bridges. The primary difference between the two full-scale models was their span lengths (300 feet and 525 feet) and the use of continuity tendons. The influence of vertical earthquake motion and the pre-earthquake stress on the seismic response of segment joints was investigated.

Seismic Concerns

The primary seismic concerns regarding segmental construction are focused on the behavior of joints between segments as no mild reinforcement crosses such joints. The lack of reinforcement across segment joints allows for an increased rate of construction, yet creates inherent regions of weakness that act as crack initiators and can result in large localized rotations. Thus, bridge owners, such as Caltrans, have questioned the response of segment joints during a seismic event in recent years. Do these joints open during an earthquake? Do they remain open after the earthquake? Does the joint opening affect shear transfer across the joints, thereby affecting dead load carrying capacity? Does joint opening alter the serviceability of the bridge? Do volumetric changes, such as creep and shrinkage, affect the joint response? These are the questions that have hampered the use of precast segmental bridges in seismic regions of the United States, namely California.

Research Objectives

The research presented in this study will: 1) quantify the impact of vertical earthquake motion on the segment joint response; 2) determine if segment joints are likely to open when full longitudinal post tensioning is considered along with vertical accelerations and will quantify the magnitude of the crack width if they do open; 3) compare the segment joint response to concrete and post-tensioning (PT) performance limit states, such as cracking, crushing, and yielding, and assess the level of joint damage during a seismic event; 4) quantify residual crack widths and; 5) assess the impact of the pre-earthquake stress-state on the response of segment joints.

JOINT MODEL VALIDATION

To ensure that the full bridge earthquake simulations accurately represent the physical world, the joint modeling approach must be validated with physical experiments. To this end, detailed finite element models of test unit 100-INT from the Phase I experiment by Megally et al., 2002 (see Figure 1), were created using the computer software Ruaumoko (Carr, 2004). Ruaumoko was selected because of its extensive library of nonlinear hysteretic and damping rules. These models were developed to emulate numerous physical characteristics of the segment-to-segment joints. These characteristics include: crushing of extreme concrete fibers; yielding of tendons at the true limit of proportionality; and energy dissipation due to bond slip of the grouted internal tendons. This modeling approach was similar to a fiber model at the segment joints with nonlinear elements for the concrete and the post-tensioning tendons across the segment joints (see Figure 2). Typically nine concrete elements and three PT elements per tendon were used to model the superstructure section across each segmental joint. This modeling approach matched the experimental results very well (see Figure 3) and is documented in greater detail in Veletzos, 2007.

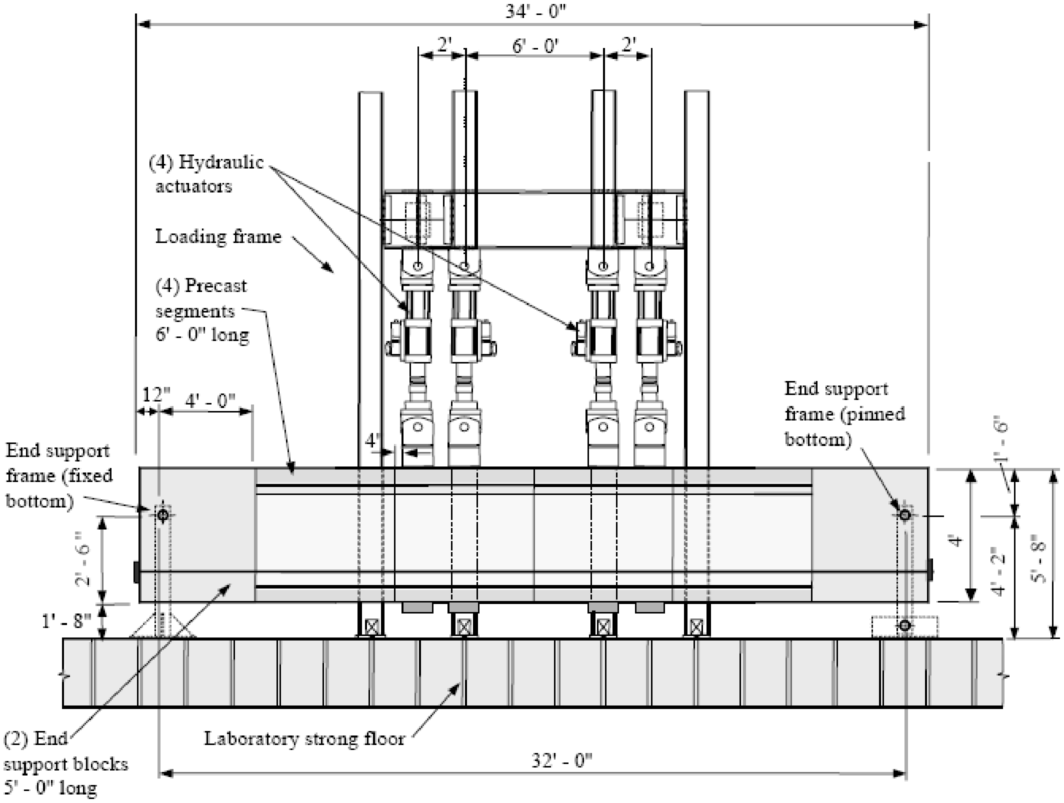


Figure 1 Phase I Experimental Test Set-Up (Megally et al., 2002)

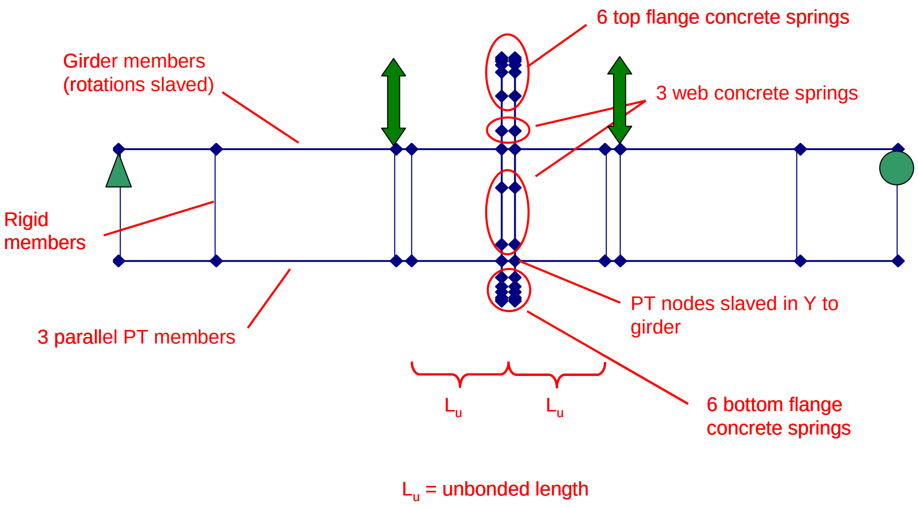
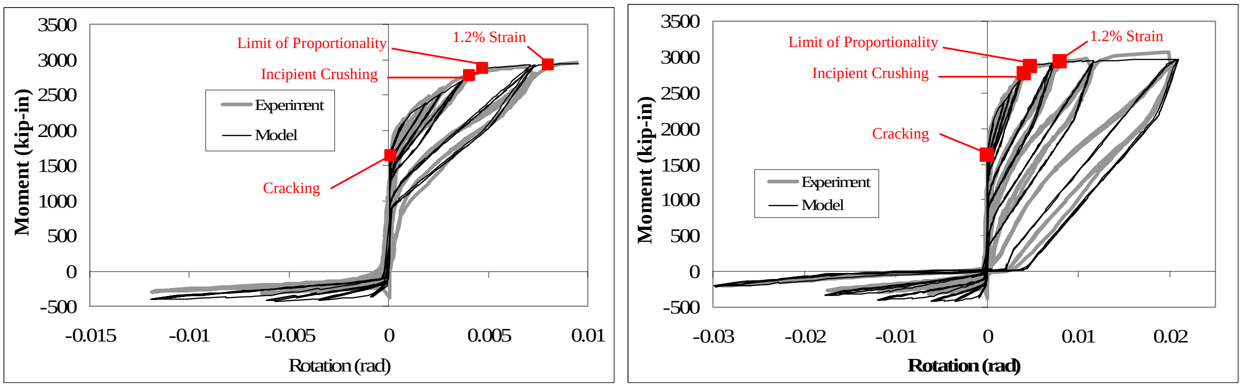


Figure 2 Single Joint Validation Model



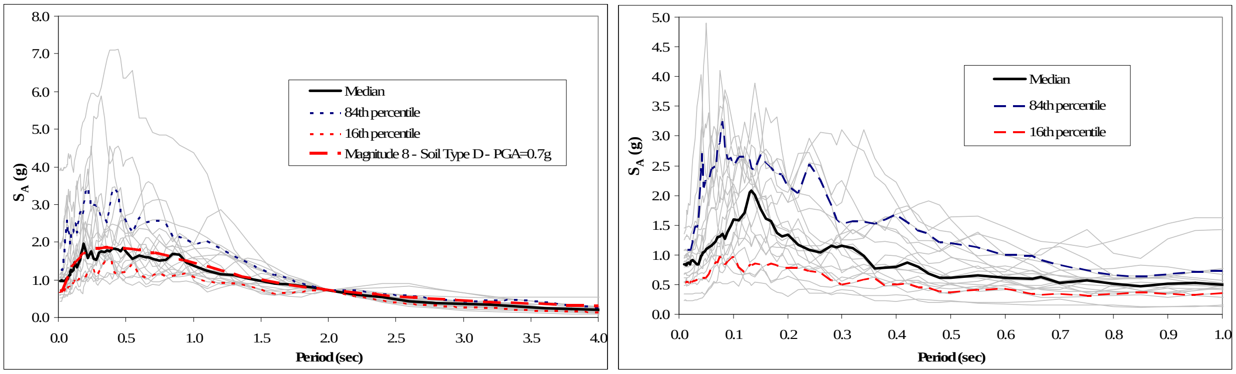
a) Small Rotations

b) Large Rotations

Figure 3 Moment-Rotation Diagrams from Joint Validation Model

EARTHQUAKE EXCITATIONS

Twenty earthquake ground motion records were selected as input into the full scale bridge models. All records were from stations that were within 15 miles (25 kilometers) of the fault rupture surface and several of the ground motions included significant near field effects (i.e. fling and forward directivity). These ground motions were amplitude to match the design spectrum at the primary longitudinal natural period of the structure (see Figure 4). This same scale factor was used on the vertical ground motion. The design spectrum (M8, 0.7g, Soil Type D) was selected from the Caltrans Seismic Design Criteria (Caltrans, 2006) and represented a 5% in 50 year (approximately 1000 year return period) seismic event.



a) Longitudinal Acceleration b) Vertical Acceleration

Figure 4 Earthquake Response Spectrum

FULL BRIDGE MODELS

Two full scale bridge models were developed to study the seismic response of superstructure segment joints. One with nominal interior span lengths of 300 feet and the other with spans lengths of 525 feet. Both bridge models were assumed to use the balanced cantilever construction method as this method will be the most economical for the span lengths considered. The models were developed based on design and construction details from segmental bridges recently constructed in California. These models, however, did not intentionally represent the actual bridges.

This paper will focus on the results and characteristics of the 300 foot span model due to space considerations and because the general results and conclusions were the same for the two span lengths. The complete results of both span lengths are presented in Veletzos, 2007.

300 Foot Span Model Discretization

The 300 foot span model was based on details of the Otay River Bridge, in San Diego County, California, which opened to traffic in November 2007. An analytical model of a five span frame was developed as shown in Figure 5. The interior spans are 297 feet and the exterior spans are 176 feet. Approximately 40% (i.e., 11 of 29 joints per span) of all superstructure segment joints were modeled.

The top and bottom of the piers were modeled with non-linear 2-component Giberson beam elements to simulate potential plastic hinges. Non-linear longitudinal abutment behavior was modeled based on recommendations in the Caltrans SDC (Caltrans, 2006).

A typical pier cantilever for a 300 foot span is shown in Figure 6. Twenty-eight superstructure segments formed the 300 foot span, thus there were twenty-nine segment joints per span. Eleven of these segment joints were modeled; six segment joints at each pier and five segment joints at midspan.

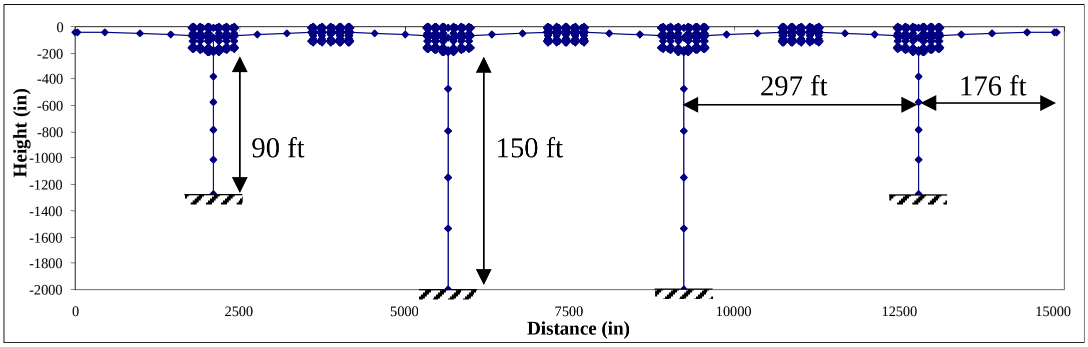


Figure 5 300 Foot Span Model (not to scale)

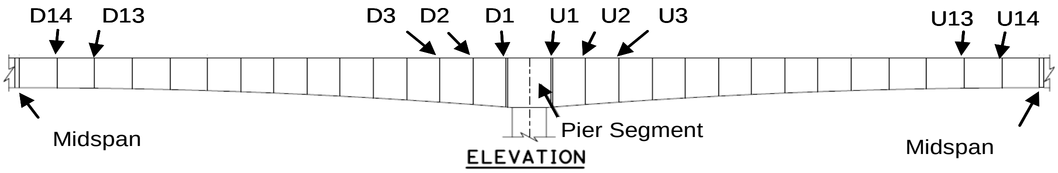


Figure 6 Segment Joint Identification

Pre-Earthquake Stress Considerations

The pre-earthquake stress-state of the structure depends on the construction method and on creep, shrinkage and temperature variations. To accurately estimate the effect of all these variables on a structure where every segment is constructed at different times and the loading at each segment joint changes during the construction process, clearly requires a very detailed analysis. Thus, the results from a full longitudinal construction staging analysis (LCA) of the Otay River Bridge were obtained from the designers, to ensure that the pre-earthquake stress-state of the segment joints were realistic.

Equal and opposite redistribution forces (i.e. bending moments and axial forces) were applied across each segment joint in the analytical model (see Figure 7), to accurately represent the stress-state of the joints after construction. The magnitude of these forces was iterated until convergence with the designer's stress-state was achieved.

To study the effect of the pre-earthquake stress-state on the seismic response, several pre-earthquake stress-states were investigated. These stress-states were developed in a systematic fashion based on the effect of creep and shrinkage. The changes in the stress-state due to creep and shrinkages of each segment joint were obtained from the LCA. This change in stress was used to generate four different pre-earthquake stress configurations that were intended to represent the range of stresses that may occur during the life of the superstructure. The four pre-earthquake stress states considered are shown in TABLE I.

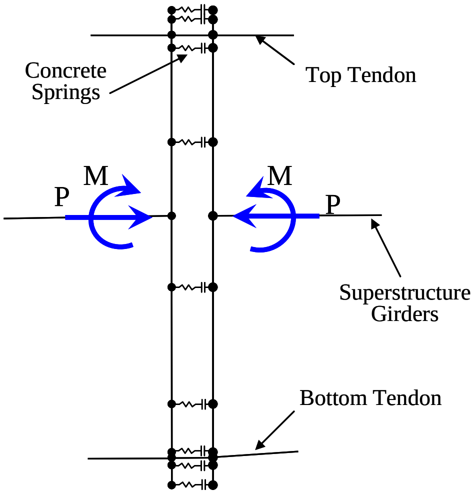


Figure 7 Sketch of Applied Segment Joint Forces

TABLE I. PRE-EARTHQUAKE STRESS STATES

Pre-EQK Stress State	Description
-CS	The stress at end of construction minus the change in stress due to creep and shrinkage. This stress configuration represented a potential state of stress near the end of construction (i.e., beginning of service life) with considerations for possible inaccuracies in the LCA as well as for considerations for the effect of temperature gradients on the bridge superstructure.
EOC	The best estimate of the stress-state at the end of construction and considers construction staging effects as well as volumetric changes that occur during construction.
+CS	The best estimate of the state of stress after the majority of creep and shrinkage has occurred, i.e., after approximately ten years of service. This stress-state also considered the effects of relaxation but the majority of the stress changes occurred from creep and shrinkage.
+2CS	The stress at EOC plus twice the change in stress due to creep and shrinkage. This stress configuration represented a potential stress-state after ten years of service life with considerations for possible inaccuracies in the LCA and creep and shrinkage calculations as well as for considerations for the effect of temperature on the bridge superstructure.

Segment Joint Performance Limit States

Vertical pushover analyses were performed to obtain the backbone curve for the moment-rotation behavior of each segment joint, and to identify the rotation where various performance limit states occurred. The limit states of interest were cracking of the section, incipient spalling of the extreme concrete fibers, the limit of proportionality of the main PT tendons which was assumed to occur at a stress of 210 ksi, and a strain of 1.2% in the main PT tendons. The consequences of the various performance limit states are outlined in TABLE II.

TABLE II. PERFORMANCE LIMIT STATES

Limit State	Description	Consequences
C1	Concrete cracking, $\varepsilon_c = 0.000012$	Onset of joint opening No consequences
C2	Incipient spalling of extreme concrete fibers, $\varepsilon_c = -0.003$	**Operational performance level** Patching of concrete may be required,
MT1	Limit of proportionality (210 ksi) of main tendons	**Operational performance level** End of purely elastic region of PT. Begin to lose prestressing force .
MT2	$\varepsilon_{pt} = 0.012$ in main tendons	**Life safety performance level** Full tendon yielding. Lose significant PT force. Residual joint openings are likely.

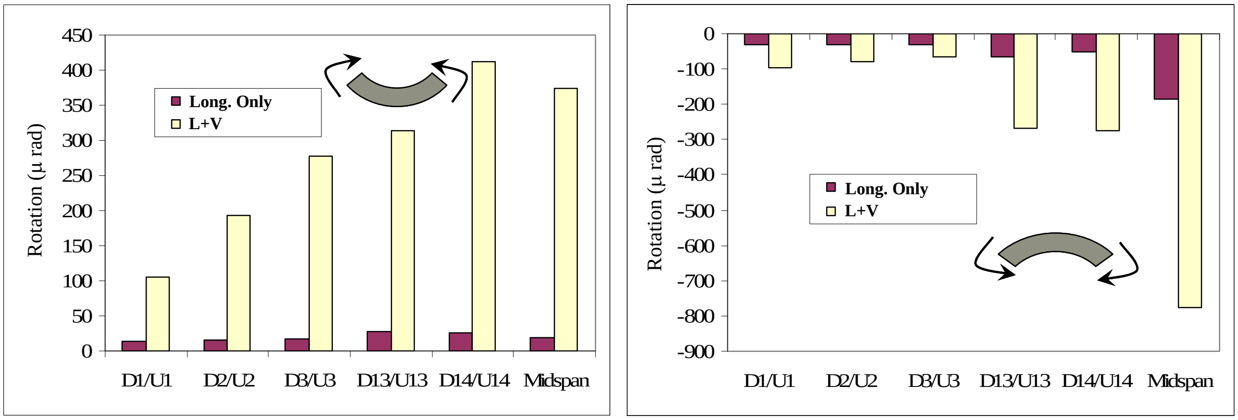
FULL BRIDGE MODEL RESULTS

Vertical Excitation

To quantify the contribution of the vertical ground motion on the segment joint response, the models were subjected to longitudinal motions only, as well as simultaneous longitudinal and vertical earthquake motions.

The effect of vertical excitation on the median peak positive bending joint rotations for the six segment joints families of the 300 foot span model is shown in Figure 8a. D1/U1 represents the first joint down-station or up-station from the pier, while D14/U14 is fourteen segment joints away from the pier and is adjacent to midspan, see Figure 6. Each vertical bar represents the median response of the twenty earthquakes due to longitudinal only (“L_only”) and due to both longitudinal and vertical (“L+V”) ground motions. It is clear that adding the vertical ground motion component significantly increases the joint rotation demand. By taking the median of the ratio of the “L+V” and “L_only” segment joint median responses, we find that the median positive bending rotations increased by 1000%. From Figure 8b, we find that median negative bending rotations increased by 250%.

The reason for such large increases in the peak rotations can be explained by comparing the joint rotation data to the performance limits states as shown in Figure 9. Each small dot represents the peak rotation from one earthquake. The square mark represents the median rotation. The diamond marks represent the 16th and the 84th percentiles and the vertical lines identify the various performance limit states. Clearly, adding the vertical earthquake ground motion pushed the superstructure joints well beyond the cracking limit state, C1, and into the non-linear range, were a small increase in bending moment produces a large increase in rotation.



a) Median Peak Positive Rotations b) Median Peak Negative Rotations

Figure 8 Influence of Vertical Ground Motion on the Median Peak Positive Segment joint Rotations

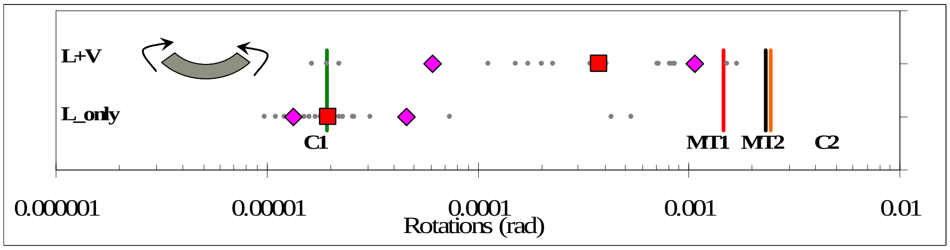


Figure 9 Influence of Vertical Ground Motion on Positive Midspan Rotations

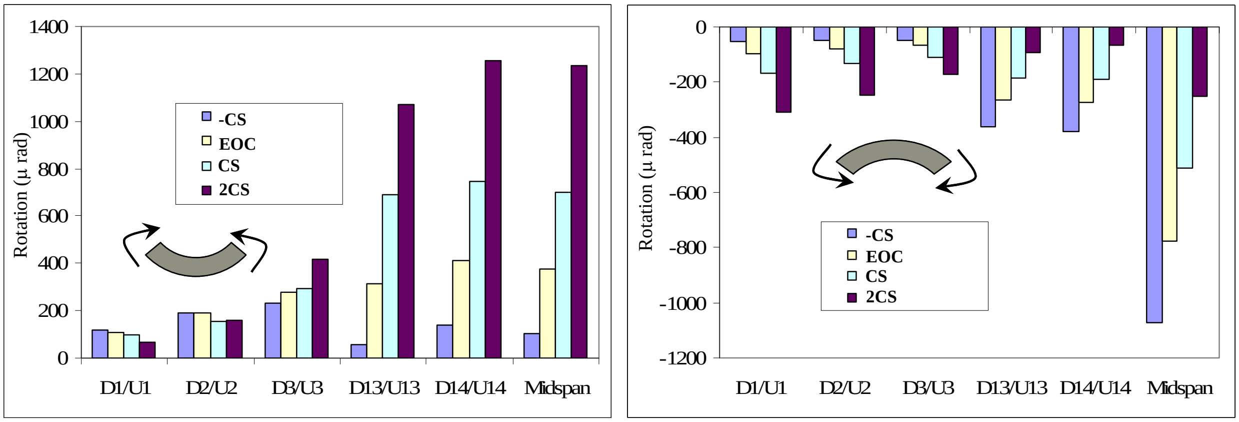
Pre-Earthquake Stress-State

Figure 10 compares the median segment joint rotations among the various joint families for the four pre-earthquake stress-states. Figure 10a presents the median response of the peak positive bending joint rotations. Clearly, the pre-earthquake stress-state impacts the joint response, particularly near midspan, where the 2CS stress-state exhibited the largest rotations. This is because the bottom of the midspan joint was under the least compression during pre-earthquake stress-state 2CS, and was the closest of the four pre-earthquake stress-states to opening under positive bending.

Figure 10b presents the median response of the peak negative bending joint rotations. Once again the midspan joints were the most impacted by the pre-earthquake stress-state, with the –CS stress-state generating the largest midspan rotations. This is because the top of the midspan joint was under the least compression for stress-state -CS, and was closest to opening under negative bending.

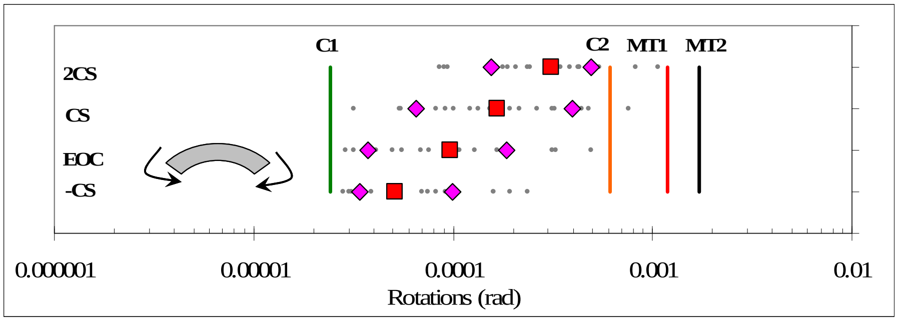
Figure 11 compares the peak negative rotations based on the four pre-earthquake stress conditions with the performance limit states for the first joint adjacent to the piers, i.e., Joint D1/U1 and the midspan joint. The absolute value of the negative rotations was taken so that the results could be plotted on a log scale. In general, the median response stayed below the limit of proportionality, MT1 and the incipient spalling limit state. However the variation in median rotation demands between different pre-earthquake stress states was very large. The largest rotation demand was at times ten times larger than the smallest rotation.

The median positive, negative and residual joint rotations, for the worst cast pre-earthquake stress state are summarized on the monotonic push results in Figure 12. These figures also indicate the performance limit states, thus the approximate level of damage is also shown in these figures. In general, the first joint adjacent to the pier and the joint at midspan exhibited the largest rotation demands and the most damage.

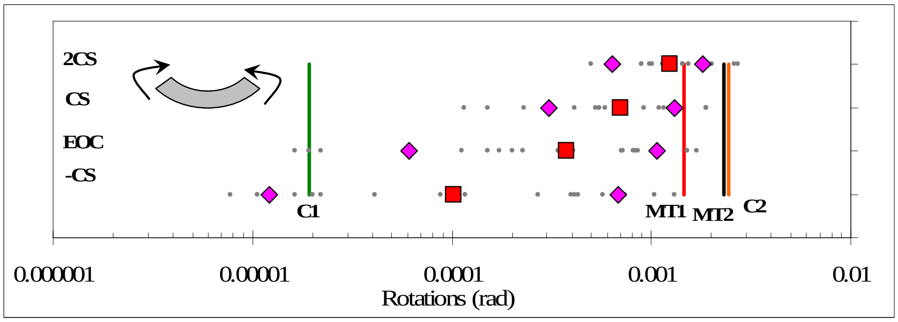


a) Median Peak Positive Rotations b) Median Peak Negative Rotations

Figure 10 Influence of Pre-Earthquake Stress-State on Segment Joint Rotations

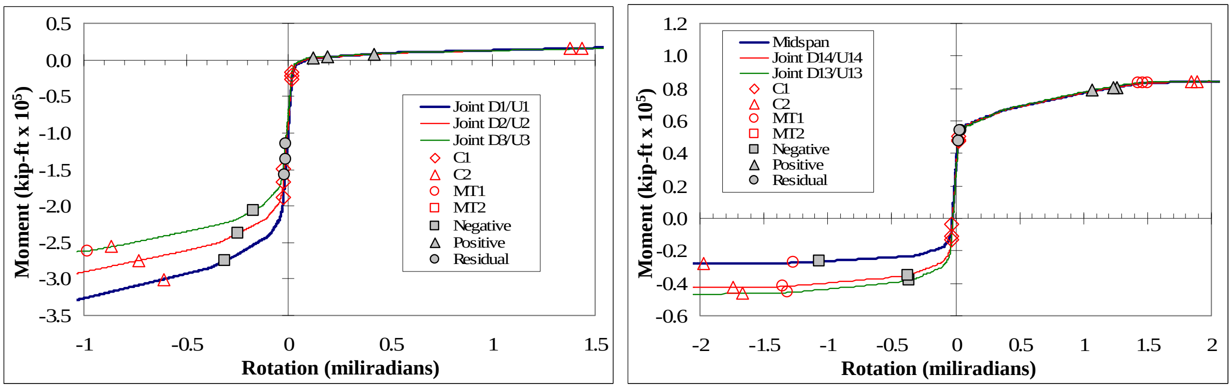


a) Joint D1/U1 Negative Rotations



b) Midspan Positive Rotations

Figure 11 Influence of Pre-Earthquake Stress on Peak Rotations



a) Adjacent to the Pier b) Near Midspan

Figure 12 Summary of Median Joint Response for Worst-Case Pre-EQK Stress-State

CONCLUSIONS

Contribution of Vertical Earthquake Motions

The results indicated that vertical earthquake motions significantly contributed to the joint response, and increased the peak negative moment joint rotations by over 1000%, the peak positive moment rotations by at least 250%, yet did not affect the residual rotations. Segment joints in positive bending near midspan experienced the largest rotation increases due to vertical ground motions. These large increases were generated because the vertical ground motion pushed the joints beyond the cracking limit state and into the non-linear range.

Joint opening

- The median segment joint rotation results showed that the segment joints exceeded the cracking limit state and opened gaps at the extreme fibers of the superstructure during a significant seismic event. In general, the first joint adjacent to the pier and the joint at midspan exhibited the largest rotation demands. Gap widths adjacent to the piers and near midspan may be up to 0.05 inches and 0.15 inches, respectively. All segment joints closed completely upon completion of the seismic event.

Performance Limit States

The results showed that the median response of the superstructure segment joints remained below the incipient spalling limit state and within the limit of proportionality of the PT. However the magnitude of the joint response varied greatly depending on the pre-earthquake stress-state.

Pre-Earthquake Stress-State

The results indicated that the pre-earthquake stress-state can influence the seismic response of segment joints by as much as one order of magnitude. This finding is contrary to common knowledge that volumetric changes have negligible effects on the structure's response to earthquakes. The extreme stress-states (i.e. -CS and +2CS) generated the largest rotation demands as observed in Figure 10 and Figure 11. This was because the extreme stress-state required the smallest seismic rotation demand to exceed a performance limit state.

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