THE INFLUENCE OF TRANSVERSE EARTHQUAKE MOTION ON THE SEISMIC RESPONSE OF PRECAST SEGMENTAL BRIDGE SUPERSTRUCTURES

Timothy J. Blair, EIT, Dept. of Civ. Eng., Merrimack College, North Andover, MA
Maxwell A. Johnson, EIT, Dept. of Civ. Eng., Merrimack College, North Andover, MA
Marc J. Veletzos, PhD, PE, Dept. of Civ. Eng., Merrimack College, North Andover, MA

ABSTRACT

Seismic design guidelines have been developed for Caltrans that address the jointed nature of segmental bridges and may increase the use of precast segmental bridge construction in high seismic zones. These guidelines were based on 2D simulations and assumed that peak vertical and horizontal response did not occur simultaneously. The combined effects of vertical and horizontal ground motion may result in segment joint opening beyond critical limit states. Thus there is a need to verify the 2D assumption inherent in the guidelines. This ongoing research project investigates the influence of transverse earthquake motion on the seismic response of precast segmental bridges with bonded tendons constructed with the balanced cantilever construction method, using detailed 3D nonlinear time history analyses. The models utilized geometries and characteristics similar to the Otay River Bridge in California and were subjected to a suite of earthquake ground motions. Preliminary results indicate that the transverse ground motions dominate the segment joint response and that adding vertical ground motion to the horizontal motions (i.e. longitudinal and transverse) increase the segment joint response by 14%. These modest increases suggest that the assumption inherent in the guidelines appear to be valid.

Keywords: Accelerated construction, Connection, Segmental bridge

INTRODUCTION

PRECAST SEGMENTAL CONSTRUCTION

Precast segmental construction is a construction method in which the bridge, typically the superstructure, is divided into individual segments. These segments are usually fabricated off site in a controlled environment and shipped to the job site. The segments are connected to each other with high strength steel post-tensioning (PT) cables, collectively known as tendons. The surface between segments is epoxy coated to prevent water from entering the joints and minimize maintenance.

The controlled construction environment of the superstructure segments often results in improved quality control and can allow for superstructure and substructure construction tasks to occur simultaneously. Thus the overall construction schedule is compressed and often results in reduced construction costs. As a result of these benefits, precast segmental bridge construction has proven to be a very effective method for spanning deep valleys, long water crossings, and environmentally sensitive regions. In addition segmental bridge construction has been deemed very suitable for many applications in highly congested urban areas where construction can result in significant traffic disruption.

There are numerous segmental construction methods that utilize both precast and cast-in-place techniques. These construction methods include: span-by-span; progressive cantilever; balanced cantilever; and incremental launch. Segmental construction methods are typically economically competitive for spans of 200-350 ft. This span range is most suitable for the precast balanced cantilever construction method. In the precast balanced cantilever construction method (see Figure 1), superstructure segments are placed one at a time beginning at the piers and proceeds outward towards midspan on both sides simultaneously. As construction progresses the negative moment on each cantilever increases, thus PT tendons are required most at the top of the section near the piers. Eventually the cantilevers from adjacent piers meet at midspan and are connected with a closure joint or an expansion joint.

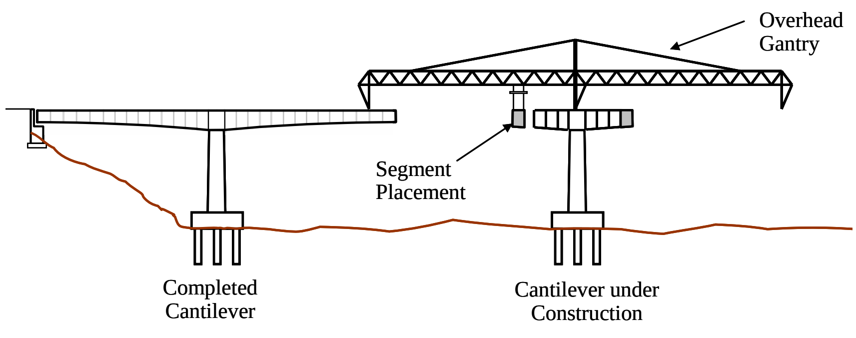


Figure 1. Schematic of Balanced Cantilever Construction with Precast Segments and an Overhead Gantry

The challenge for precast segmental construction from a seismic perspective stems directly from the fact that the superstructure is not monolithic. The jointed nature of precast segmental superstructures results in behavioral modes that differ from conventional prestressed concrete bridge and can affect the response during strong seismic shaking. Mild steel reinforcement, i.e. rebar, is often detailed only within the segments themselves, creating regions of discontinuity at the segment joints. Such discontinuities act as crack initiators and typically confine cracking to the segment joints. Strong seismic shaking may cause inelastic behavior to concentrate at a single segment joint in the superstructure and may result in inelastic behavior that exceeds critical limit states.

PROBLEM STATEMENT

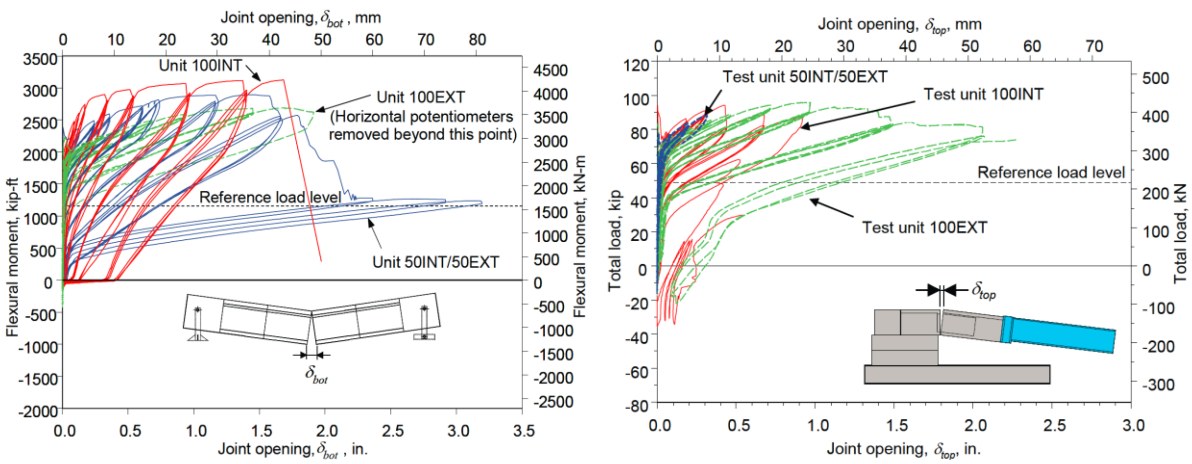
Seismic design guidelines have recently been developed for the California Department of Transportation (Caltrans) that address the jointed nature of segmental bridges[1]. However these guidelines were based on 2D simulations and assumed that peak vertical and horizontal response did not occur simultaneously and thus can be neglected. This assumption has not been confirmed. It may be the case that the effects of vertical and horizontal ground motion combine to increase segment joint opening beyond critical limit states and prevent the joints from closing completely. Exceeding critical limit states such as concrete crushing and the limit of proportionality of tendons will reduce the remaining ductility capacity and may allow water to enter the segment joints that can corrode the tendons. Thus there is a need to verify the accuracy of this assumption. If it is not valid then revised seismic design guidelines are required that include recommendations on appropriate methods to model the 3D effect on segmental bridge superstructures.

RESEARCH OBJECTIVES

The objective of this ongoing study is to test the assumption that the peak vertical and horizontal segment joint response do not occur simultaneously. This objective will be accomplished through the use of detailed 3D nonlinear analyses that have been calibrated against large scale experiments.

SUMMARY OF PREVIOUS RESEARCH

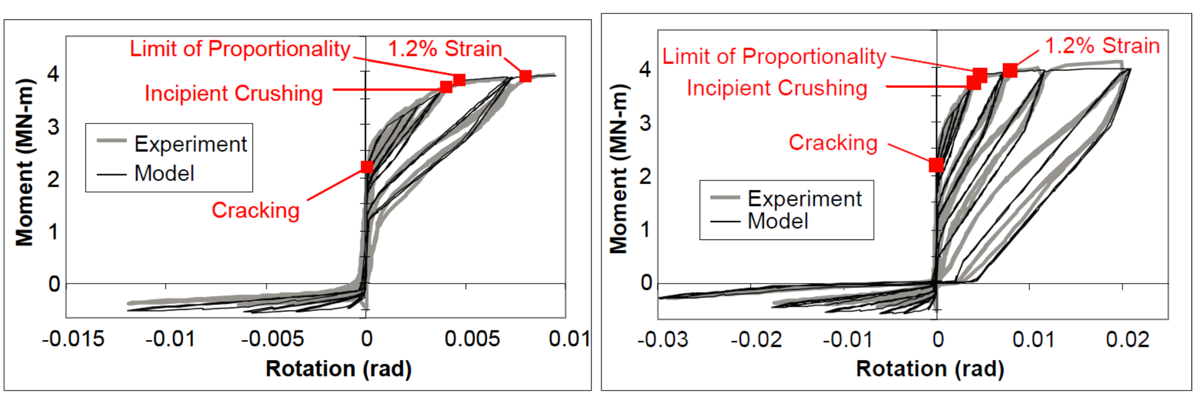
Numerous studies have been conducted in recent years related to the seismic response of precast segmental bridges. These studies included large scale experiments on precast segmental bridges superstructures that investigated the segment joint behavior as well as studies investigating appropriate methods to model this behavior. The large scale experiments investigated different PT tendon configurations and the performance of both midspan and pier segment joints[2]. Figure 2 shows the segment joint response from these experiments and indicates that precast superstructure segment joints can exhibit significant nonlinear behavior prior to failure. They also indicate that residual joint openings are possible if significant nonlinear joint response is obtained.



a) Midspan Joints b) Pier Joints

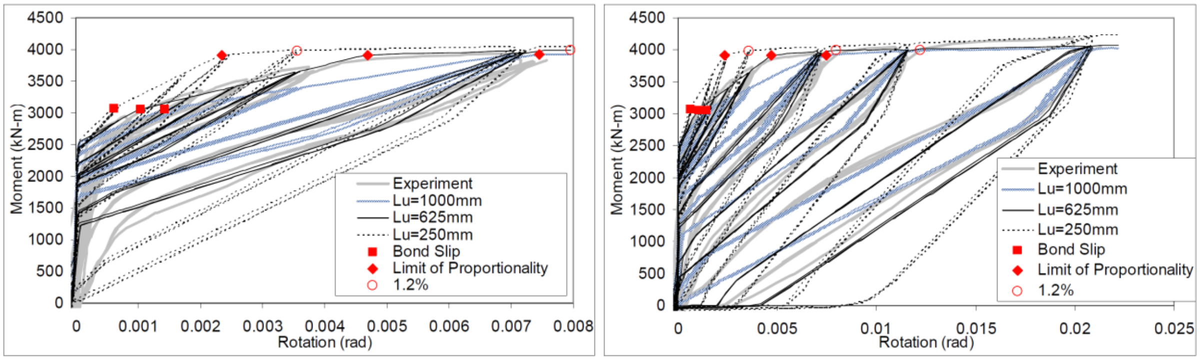
Figure 2. Segment Joint Response from Large Scale Experiments[2]

Building upon these large scale experiments, component level finite element segment joint models were developed to determine appropriate modeling techniques that can capture the unique behavior of precast segmental concrete joints. These studies determined that superstructure segment joint response can be accurately modeled using discrete nonlinear elements that represent the concrete and PT tendons at a segment joint.[3] Figure 3 compares the large scale experimental results with the finite element segment joint model. In addition, these studies identified the parameters that impact the response of segment joints. One important parameter is the equivalent unbonded length of the PT tendon (see Figure 4). As the segment joint opens, the bonded tendon will begin to debond. Inaccurate estimates of the equivalent unbonded length, L_u, will result in inaccurate estimates of the post opening joint stiffness and inaccurate estimates of the joint rotational response, which will ultimately result in poor estimates of the concrete and PT tendon strains.[3]



a) Small Rotation b) Large Rotations

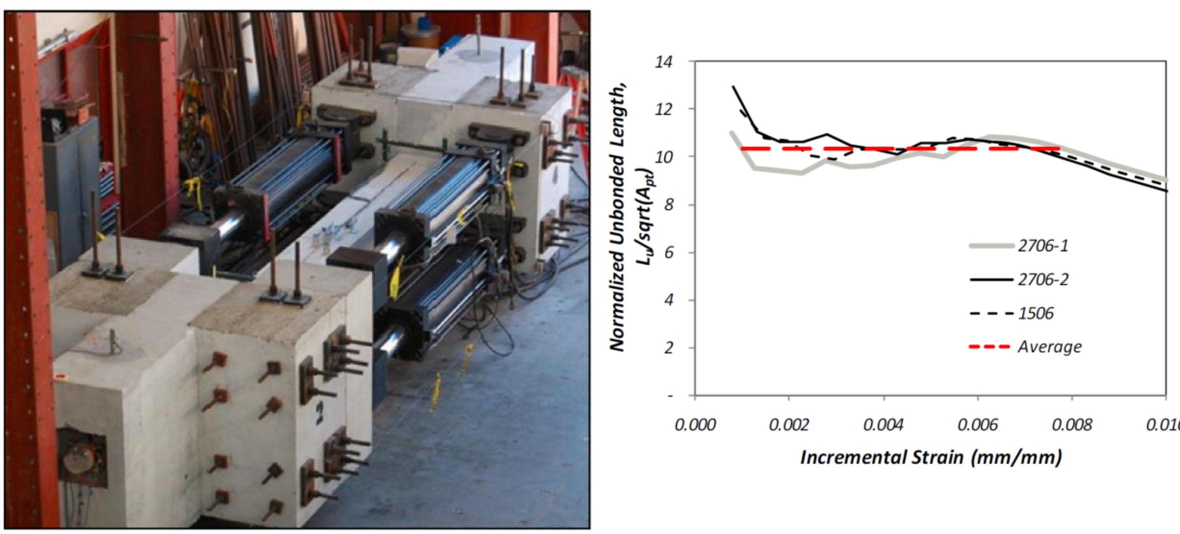
Figure 3. Comparison of 2D joint model with large scale experimental results.[3]



a) Small Rotation b) Large Rotations

Figure 4. Sensitivity of joint model response to the unbonded length, L_u, of PT tendons.[3]

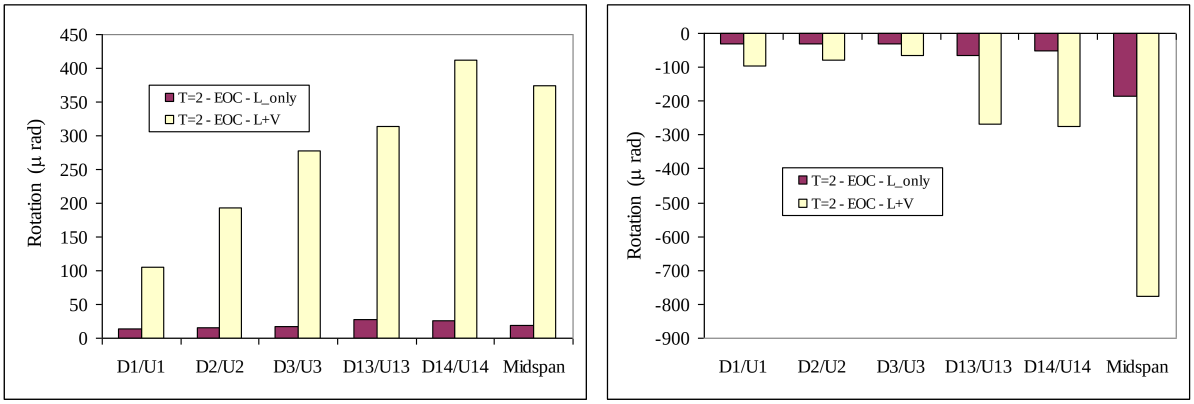
The segment joint model calibration studies shown in Figure 3 were developed based on a trial and error approach to define the appropriate equivalent unbonded length. This approach is sufficient when attempting to calibrate a model to a specific experiment, but is insufficient when attempting to model a full scale structure that does not have large scale experimental data. Thus studies on full scale tendons were performed to determine an equation that will adequately predict the equivalent unbonded length of bonded PT tendons (see Figure 5). These experiments showed that the equivalent unbonded length is proportional to 10.3 times the square root of the cross section area of the tendon and is independent of the grout strength and the concrete strength.[4]



a) Test Set-up b) Normalized Unbonded Length vs Incremental Strain

Figure 5. Large Scale Experiments to determine an equation for the equivalent unbonded length, L_u, of PT tendons[4].

Studies on the 2D response of full scale bridge systems that incorporated the component level segment joint models were also performed. These studies showed that vertical earthquake motion (see Figure 6) and the pre-earthquake stress state in the superstructure can significantly alter the seismic response of segment joints in precast segmental bridges and should be considered during the design process.[5] Additional studies investigated methods to model segmental superstructures and recommended modeling methods appropriate for "Important" and "Ordinary" bridges.[6] The results of these 2D studies were used to develop seismic design guidelines for segmental construction for Caltrans.



a) Median Peak Positive Rotation b) Median Peak Negative Rotation

Figure 6. The bar graphs show the influence of vertical ground motion on the segment joint rotations.[5]

COMPONENT LEVEL JOINT MODELING

3D component level joint models were developed based on the Otay River Bridge in San Diego County, to simulate the response of segment to segment joints. These joint models were developed in a similar manner as the models shown in Figure 3 and Figure 4, and are able to capture the bi-directional coupling effects of the segment joints and include fifteen non-linear elements that represent the concrete and PT tendons in the cross-section. To simulate a representative compressive force across the segment joints, the elements representing the PT tendons were thermally loaded. Four segment joint models were developed to represent two joints near midspan and two joints adjacent to the piers. Figure 7 shows the geometry of the segment joint closest to the pier and includes an outline of the cross-section to help visualize the segment joint. The 3D joint models were validated with XTRACT, an industry standard concrete section analysis software (see Figure 8a). This validation assumed no slip between the PT tendons and the concrete to match the limitations of XTRACT. Figure 8b illustrates the moment-curvature response of the four segment joint families and includes debonding of the PT tendons based on the expression for the equivalent unbonded length described above and illustrated in Figure 5b.

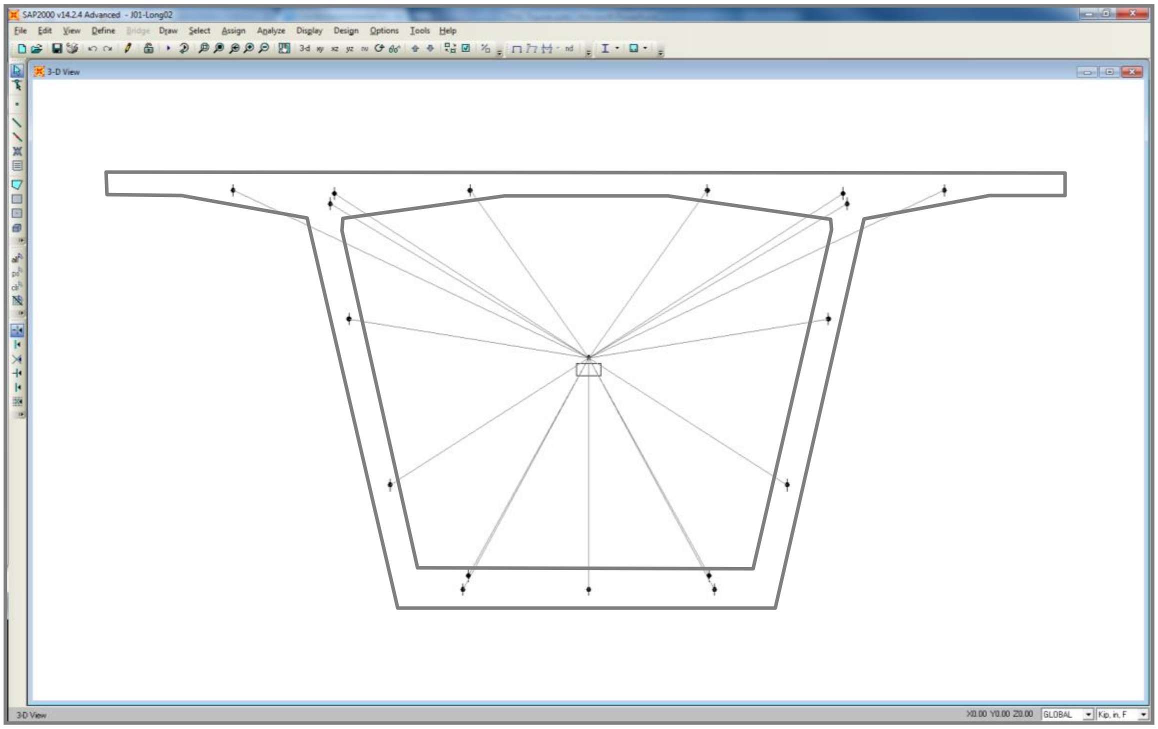
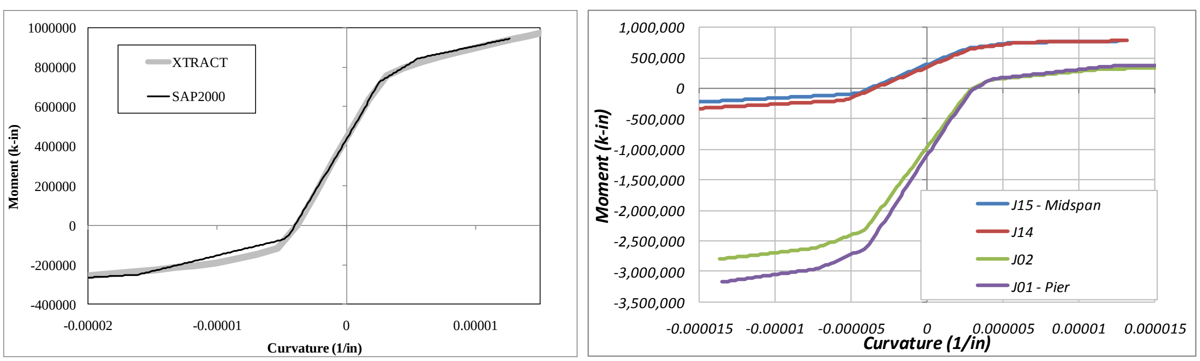


Figure 7. Screen shot of a 3D segment joint model with the cross section outlined



a) Comparison with XTRACT b) Moment-Curvature Response

Figure 8. SAP2000 Segment Joint Model

FULL BRIDGE MODELS

A 3D full bridge model was developed based on the Otay River Bridge in San Diego, CA (see Figure 9) with 300 foot typical spans. The model represents a five span segmental bridge configuration that crosses a deep ravine and was developed using SAP2000 and utilized the 3D segment joint models discussed above. These detailed 3D segment joint models were used to represent critical superstructure segment joints, that is, near midspan and adjacent to the piers, because these are the segment joints in the bridge that are expected to exhibit non-linear behavior during a strong seismic event. A total of twenty five detailed

3D joint models (four adjacent to each of the four piers, and three near midspan of the three interior spans) were incorporated into the 3D bridge model (see Figure 10). The superstructure segment joints were calibrated to a pre-earthquake stress state that represents the state of stress after the majority of creep and shrinkage has occurred. The columns include bi-directional plastic hinge elements at the top and bottom. The properties for these column hinge elements were based on moment curvature analyses and the plastic hinge length equation that is appropriate for large hollow column sections.[7]

Figure 9. The Otay River Bridge during construction in San Diego, CA.

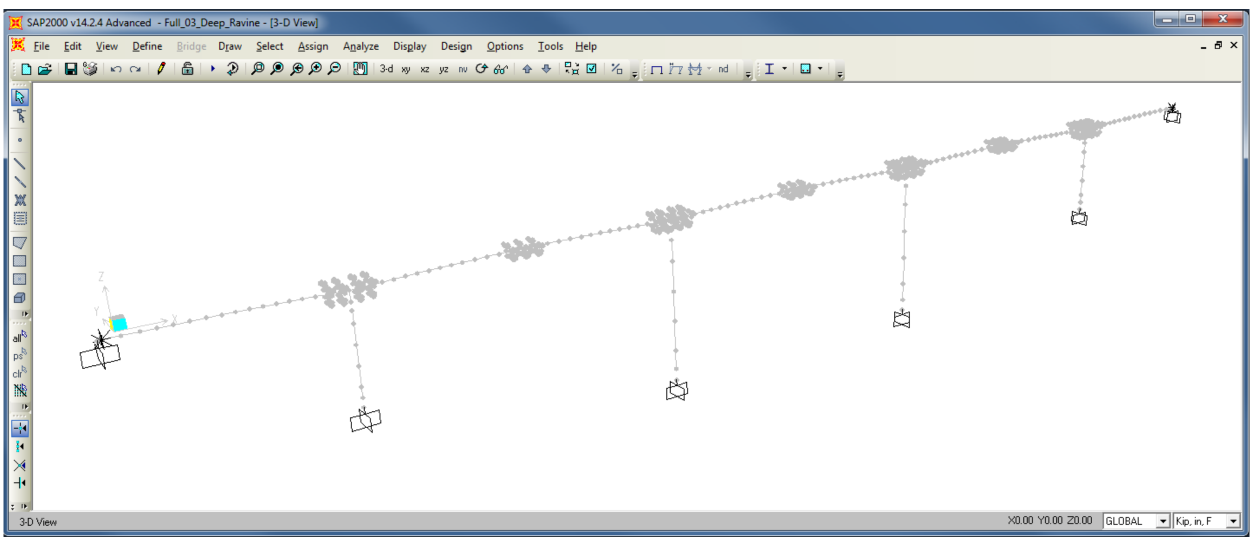
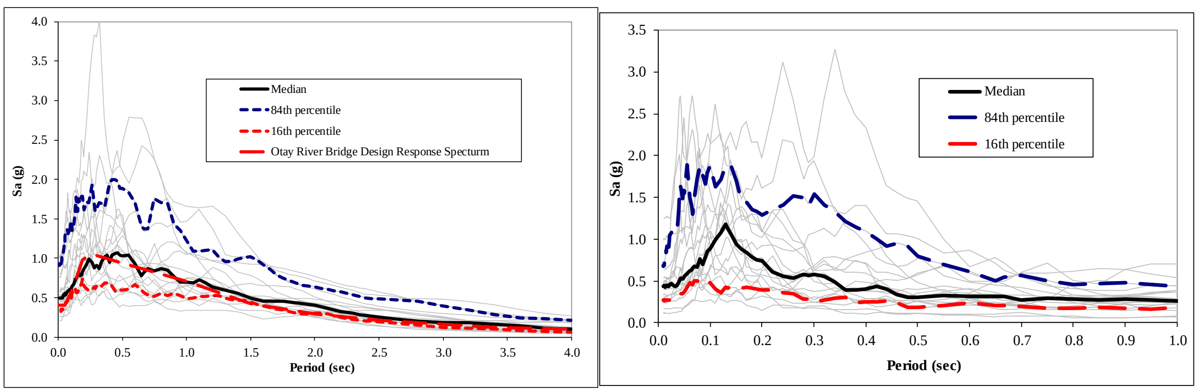


Figure 10. Screen-shot of the "Deep Ravine" 3D bridge model

EARTHQUAKE GROUND MOTIONS

Twenty near-field records were selected as input into the 3D full bridge model with the goal of obtaining the median seismic responses. All records were from earthquakes of moment magnitude 6.7 or greater and from stations within 15 miles of the fault rupture surface. Several of the ground motions included significant near-field effects (i.e. fling and directivity). Table I lists the earthquakes used and summarizes various parameters of each ground motion. These ground motions were amplitude scaled to match the Otay River Bridge design spectrum over a period range from 0.5 seconds to 2.5 seconds. To keep the components of the seismic event consistent with motions that occur in nature, the scale factor used in the horizontal ground motions was also used on the vertical ground motion. Figure 11 compares the scaled ground motion response spectra with the design spectrum for the Otay River Bridge. Figure 11a clearly indicates that the median of the twenty ground motions is representative of the design spectrum.



a) Average Horizontal Acceleration b) Vertical Acceleration

Figure 11. Earthquake Response Spectra

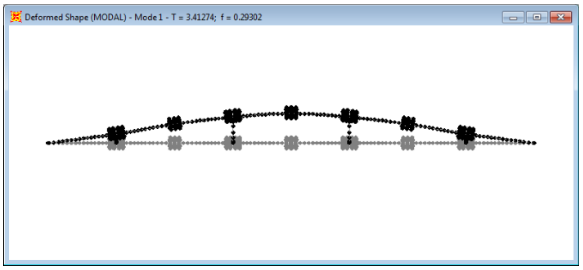
TABLE I: EARTHQUAKE GROUND MOTIONS

Earthquake	Station	Date	Mw	Closest Dist to Rupture Surface (km)	Scale Factor
Chi Chi	TCU068	9/20/1999	7.6	1.1	**0.623**
Chi Chi	TCU065	9/20/1999	7.6	1.0	**0.620**
Duzce	Bolu	11/12/1999	7.1	17.6	**1.296**
Erzincan, Turkey	Erzincan	3/13/1992	6.7	1.8	**0.959**
Iran	Tabas	9/16/1978	7.4	3.0	**0.679**
Irpinia, Italy	Calitri	11/23/1980	6.5	19.0	**2.678**
Kobe	Takatori	1/16/1995	6.9	0.3	**0.419**
Kobe	Takarazuka	1/16/1995	6.9	1.2	**0.760**
Kobe, Japan	Kobe JMA	1/17/1995	6.9	0.5	**1.396**
Landers	Lucerne	6/28/1992	7.3	1.1	**1.153**
Loma Prieta	Gilroy Historic	10/17/1989	7.0		**1.795**
Loma Prieta	Los Gatos Presentation Center	10/17/1989	7.0	3.5	**0.817**
Loma Prieta	Lexington Dam Abutment	10/17/1989	7.0	6.3	**4.503**
Loma Prieta	Saratoga Aloha Ave	10/17/1989	7.0	8.3	**1.226**
N. Palm Springs	Morongo Valley	7/8/1986	6	10.1	**1.492**
Northridge	Sylmar	1/17/1994	6.7	6.4	**0.804**
Northridge	Rinaldi	1/17/1994	6.7	7.1	**0.631**
Northridge-01	Arleta	1/17/1994	6.7	9.2	**2.778**
San Fernando	Pacoima Dam	2/9/1971	6.6	2.8	**0.751**
Superstition Hills	Wildlife Liquef.	11/24/1987	6.7	24.4	**1.043**

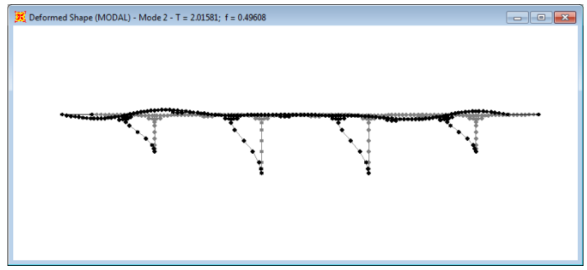
RESULTS

MODAL CHARACTERISTICS AND VALIDATION

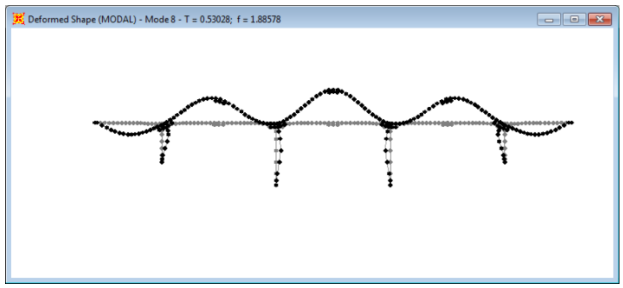
The primary mode shapes for the 3D model are shown in Figure 12. The dynamic characteristics of the model were validated against full scale models from previous research (see Table II)[5]. The moment rotation characteristic of a pier plastic hinge is shown in Figure 13 and indicates that the hinge element is functioning as desired. Figure 14 shows the longitudinal push-over response for the model and confirms that the model captures the longitudinal hinging of the piers as well as the nonlinear stiffness and capacity of the abutment back wall and the soil behind the back wall[8].



a) Primary Transverse



b) Primary Longitudinal



c) Primary Vertical

Figure 12. Primary Mode Shapes from the 3D Model

TABLE II: MODAL COMPARISON AND VALIDATION

Mode	3D Model	2D Model[5]
Primary Transverse	T=3.41 sec (63.6% mass)	Not applicable
Primary Longitudinal	T=2.01 sec (83.6% mass)	T=2.04 sec (83.5% mass)
Secondary Transverse	T=1.03 sec (10.0% mass)	Not applicable
Primary Vertical	T=0.530 sec (17.2% mass)	T=0.535 sec (17.1% mass)
Secondary Vertical	T=0.317 sec (23.0% mass)	T=0.320 sec (23.2% mass)

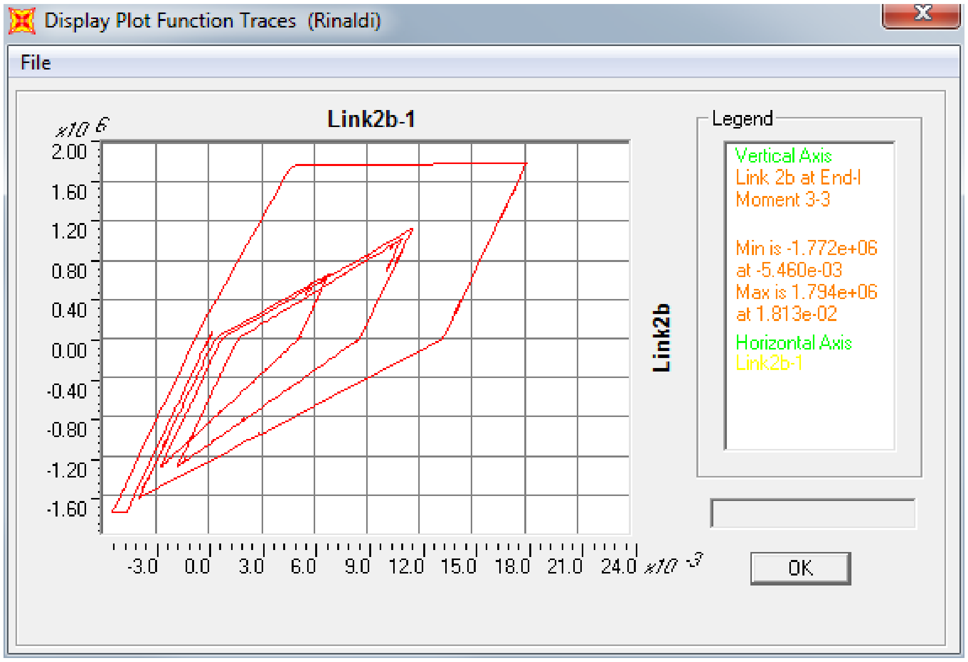


Figure 13. Moment-Rotation Response of the NLINK element at the Base of Pier 2

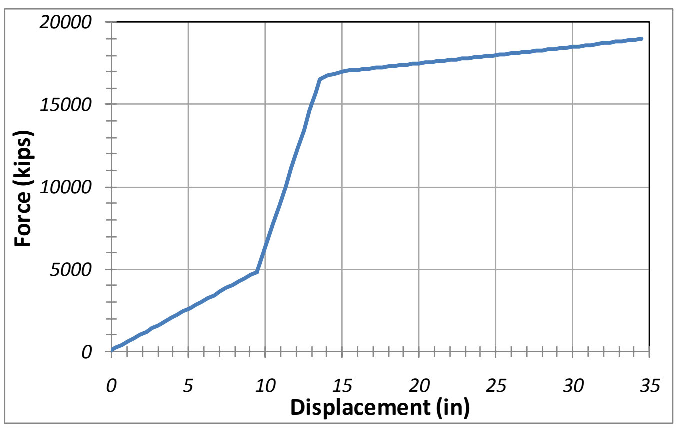


Figure 14. Longitudinal Push-Over Response of the 3D Model

3D SEISMIC RESULTS

The median response of various segment joint parameters are shown in Figure 15, Figure 16, and Figure 17 for segment joint families adjacent to the pier (i.e. J1 and J2) and near midspan (i.e. J14 and J15). The parameters include the maximum segment joint opening (Figure 15), the maximum PT strain (Figure 16) and the maximum concrete strain (Figure 17). These figures show the median response due to seven different ground motion sets: X (longitudinal) component only; Y (transverse) component only; Z (vertical) component only; X and Y components; X and Z components; Y and Z components; and X, Y and Z components. It is clear that the largest response occurs from sets that include the transverse (Y) ground motion component, particularly in the segment joints near midspan (i.e. J14 and J15). Adding longitudinal motion to the transverse alone (i.e. comparing XY to Y) resulted in no appreciable increase in the segment joint response.

Figure 15 indicates that adding the vertical ground motion component to the combined longitudinal and transverse motions (i.e. comparing XYZ to XY) increased the peak joint opening by an average of 26% and a maximum of 30%. The response across joints is fairly uniform and the maximum joint openings remain small.

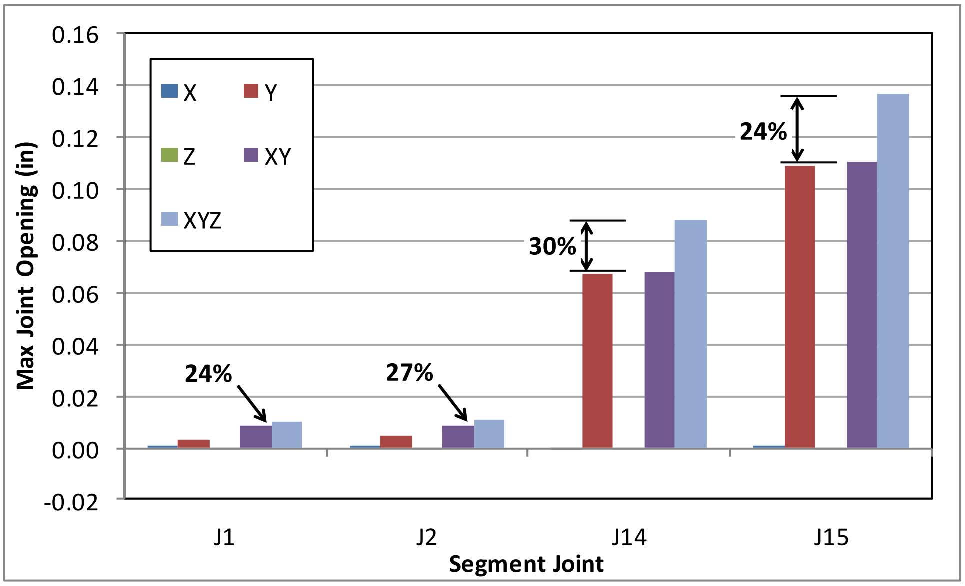


Figure 15. Median Value of the Maximum Segment Joint Opening

Figure 16 indicates that adding the vertical ground motion component to the combined longitudinal and transverse motions (i.e. comparing XYZ to XY) increased the peak PT strain by an average of 5% and a maximum of 11%. It is clear from this figure that the midspan joints (i.e. joints 14 and 15) exhibit larger strain increases than the joints adjacent to the piers (i.e. joints 1 and 2). This figure also indicates that the PT strain may exceed a strain of 1% which is commonly associated with yielding of the PT.

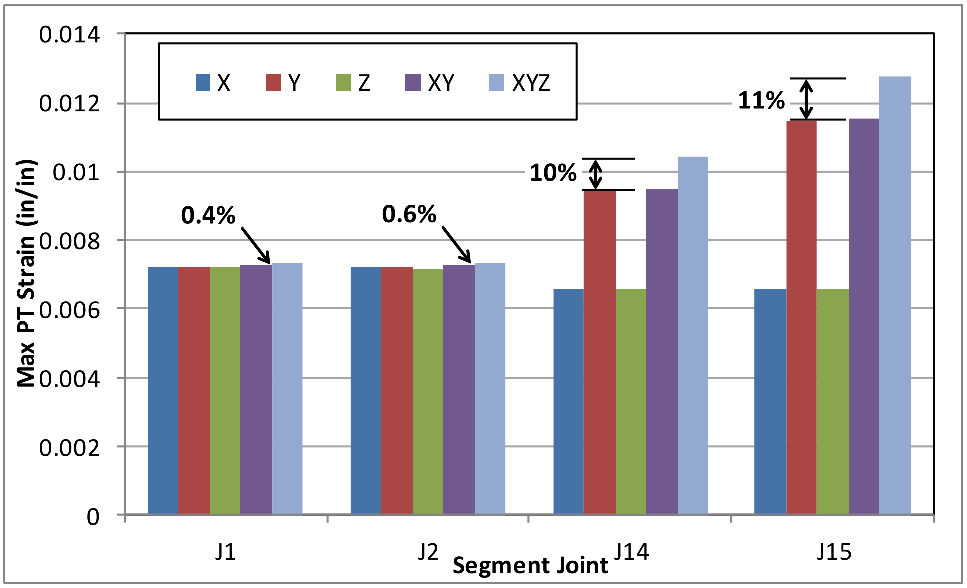


Figure 16. Median Value of the Maximum PT Strain

Figure 17 indicates that adding the vertical ground motion component to the combined longitudinal and transverse motions (i.e. comparing XYZ to XY) increased the peak concrete strain by an average of 11% and a maximum of 12%. The response across joints is fairly uniform and the maximum strains remain below 0.002 which is the strain that is commonly associated with maximum concrete stress.

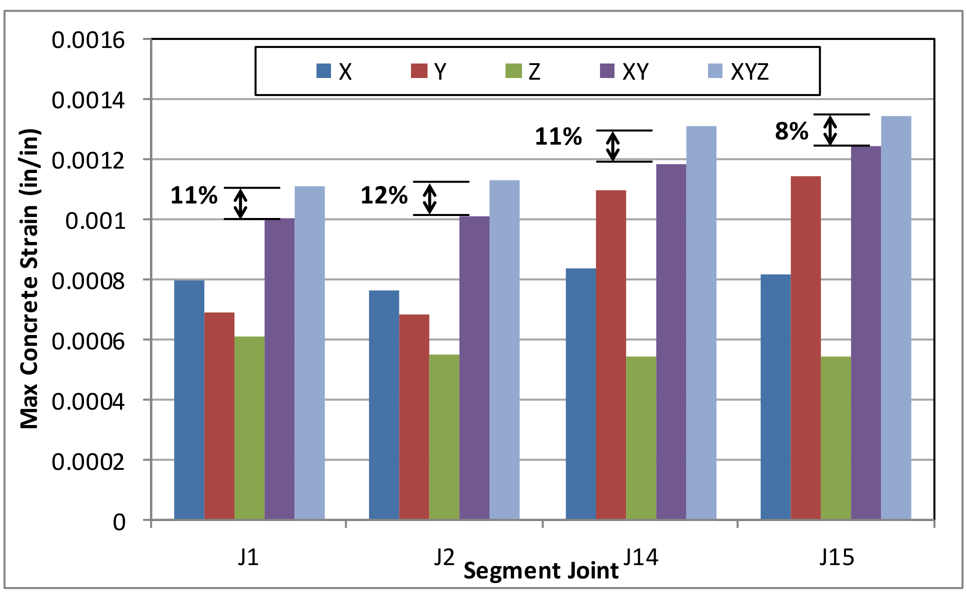


Figure 17. Median Value of the Maximum Concrete Strain

CONCLUSIONS

This ongoing research project developed a 3D full bridge model that represents a segmental bridge configuration that crosses a deep ravine. The 3D bridge model incorporated detailed 3D segment-to-segment joint models at twenty-five joints and allow for the study of the nonlinear response of segment joints due to seismic excitation. The model was subjected to five sets of twenty earthquake ground motion records to assess the impact of including the transverse ground motion on the response of superstructure segment joints and to assess the efficacy of the assumption used in recent seismic design guidelines. Preliminary results indicate that the transverse ground motions dominate the segment joint response, particularly at joints near midspan and that adding vertical ground motion to the horizontal motions (i.e. longitudinal and transverse) increase the PT strain and concrete strain by up to 11% and 12%, respectively. These modest increases due to vertical ground motion suggest that the decoupling of vertical and horizontal motions in the recent seismic design guidelines appear to be appropriate.

LIMITATIONS

This research project was based on analytical models of a precast segmental bridge with 300 foot typical spans and constructed using the balanced cantilever construction method. In addition the models simulated a five span bridge with single column bents that ranged in height from 95 feet to 150 feet and crossed a deep ravine. Bridges with different bent configurations and height patterns, such as a double column bent bridge that is part of a long viaduct, are likely to have columns of similar height and display a different transverse response. Thus the results presented herein may not be applicable to all segmental bridge configurations. This is an ongoing research project and other bridge configurations are under development to address these limitations.

ACKNOWLEDGEMENT

This research project was supported by a Merrimack College faculty development grant. The authors would like to gratefully acknowledge the hard work, dedication and contributions of undergraduate student researchers, Thomas Roby and Douglas Fischer.

REFERENCES

1. Veletzos, M.J., and Restrepo, J.I. “Development of Seismic Design Guidelines for Segmental Construction”, *Structural Systems Research Report, SSRP-2010/02*, University of California, San Diego, La Jolla, CA, December 2011.
2. Megally, S., Veletzos, M.J., Burnell, K., Seible, F., and Restrepo, J.I. “Seismic Performance of Precast Segmental Bridges: Summary of Experimental Research on Segment-to-Segment Joints”, *PCI Journal*, Vol. 54, No. 2, Spring 2009.

3. Veletzos, M.J., and Restrepo, J.I. "Modeling of Jointed Connections in Segmental Bridges", *ASCE Journal of Bridge Engineering*, Vol. 16, No. 1, pp. 139-147, January/February 2011.
4. Veletzos, M.J., and Restrepo, J.I. "Equivalent Unbonded Length for Modeling of Multi-strand Tendons in Precast Segmental Construction", ASCE Journal of Bridge Engineering, Vol. 19, No. 1, pp. 101-109, January, 2014
5. Veletzos, M.J., and Restrepo, J.I., "Influence of Vertical Earthquake Motion and Pre-earthquake stress on Joint Response of Precast Concrete Segmental Bridges", *PCI Journal*, Vol. 54, No. 3, Summer 2009.
6. Veletzos, M.J., and Restrepo, J.I. "A Case Study of Analysis Techniques for Precast Segmental Bridges Subjected to Vertical Seismic Excitation", *5th International Conference on Bridge Maintenance, Safety and Management*, Philadelphia, PA, July 2010.
7. Hines, E.M., Dazio A., and Seible, F., "Structural Testing of the New East Bay Skyway Piers", *ACI Structural Journal*, 103(1), pp. 1-10, January – February 2006.
8. California Department of Transportation (Caltrans) (2010). "Seismic Design Criteria. Version 1.6". Sacramento, CA: Caltrans.