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Nonlinear analysis of a large bridge with isolation bearings

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Abstract

As a part of the California Toll Bridge Seismic Retrofit Program, a global nonlinear time history analysis of the Benicia-Martinez Bridge was conducted using ADINA. A key component of the retrofit strategy was the implementation of friction pendulum bearings. Proper application of the frictional contact surface and the simulation of the restoring force of the bearing were critical to the evaluation of the proposed seismic retrofit. Various local models of the bearing system were developed to study its response and sensitivity to the modeling parameters. Responses of the ADINA friction pendulum bearing representation were compared to those of other nonlinear codes. The behavior predicted by the system of elements used in ADINA for the friction pendulum bearing produced results that matched very closely with other programs. Other important issues for analyzing the Benicia-Martinez Bridge are also discussed. © 1999 Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

The Benicia-Martinez Bridge spans the Carquinez Straits connecting the cities of Benicia and Martinez on Interstate Highway 680 between the counties of Solano and Contra Costa in California. Under a state mandate after the 1989 Loma Prieta earthquake, the existing Benicia-Martinez Bridge was slated for seismic retrofit improvements under the California Toll Bridge Seismic Retrofit Program.

The Benicia-Martinez Bridge represents a lifeline structure to the Bay Area. It is a critical route for traffic and commerce between the San Francisco Bay Area and the Sacramento Valley. Therefore the State of California specified in performance criteria for the retrofit design that immediately following a maximum credible earthquake event, the structure should be operational and open to the public. Implicit in this performance specification is that the structure should not collapse, and that the life safety of its users should be ensured.

The design criteria for the retrofit design of the structure were therefore based on the desired level of serviceability [1]. In terms of performance, the analysis and subsequent retrofit design of the Benicia-Martinez Bridge differs from other recent efforts associated with the California Toll Bridge Seismic Retrofit program on at least two counts. First, to meet the criteria of remaining operational after a seismic event, the retrofit design specification required that the bridge have little or no damage following the maximum credible earthquake. Secondly, the retrofit design relied heavily on the use of friction pendulum bearings—a relatively untested bearing for application to large bridge structures. To assess the retrofit design, the use of nonlinear analysis was required to account for the bearing's inherent nonlinear behavior. While such bearings have

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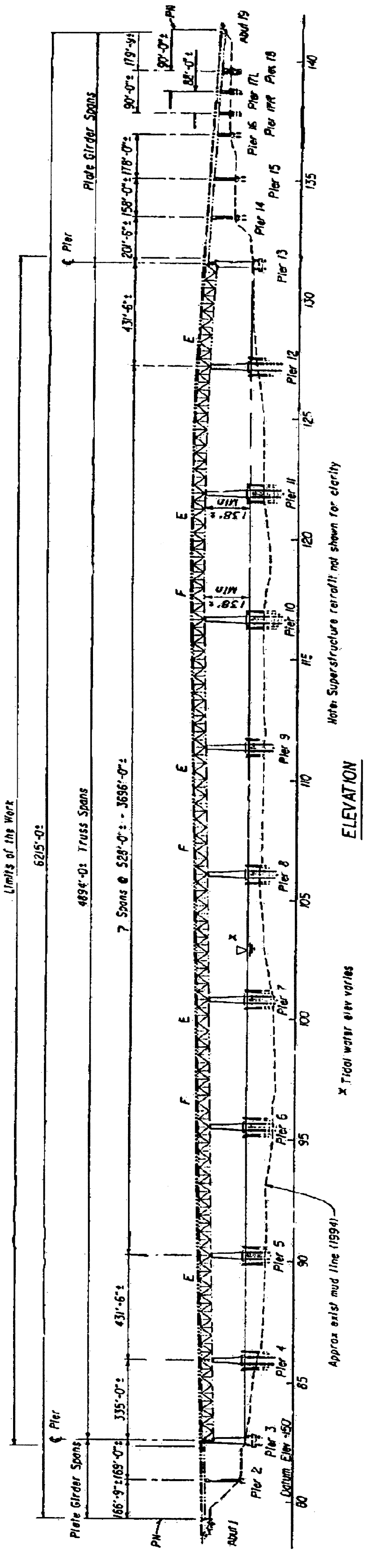


Fig. 1. Elevation view of the Benicia-Martinez Bridge.

been used on a smaller scale to retrofit and provide isolation systems for buildings, the friction pendulum bearings have rarely been used on a large scale such as required for the retrofit of a major bridge structure.

Material presented in this paper will describe the global model of the bridge and, in particular, the modeling of the friction pendulum bearings using the ADINA contact surface element, and the verification of the friction pendulum bearing simulation.

2. Description of the structure and site seismicity

The main span structure of the Benicia-Martinez Bridge consists of 11 spans totaling 4894 feet in length (Fig. 1). The superstructure is composed of a steel truss, which connects to a system of floor beams and stringer beams to a concrete deck. The substructure consists of multi-celled concrete box piers, which are founded on caissons.

The input ground motions, foundation damping and stiffness matrices were provided by the geotechnical consultant for the project. The ground motions were developed for each pier in each of the three orthogonal directions. The displacement time histories were used as input to the global ADINA model. The motions were filtered through the foundation damping and stiffness matrices. The Green Valley Event was used as input to assess the adequacy of the retrofit design [2].

3. Performance criteria and retrofit strategy

The retrofit strategy implemented for the Benicia-Martinez Bridge was developed based on the performance criteria set forth by the State of California. The criteria required that the bridge remain serviceable to emergency vehicles and the public immediately following a major seismic event. This criterion implied that damage to the structure should be kept to a minimum, such that the bridge would not pose any safety or access issues to its users following a major earthquake.

The basic principle behind the subsequent retrofit strategy was that of isolating the superstructure from the substructure to minimize the damage to the important load carrying elements in the superstructure and allow the substructure to undergo large displacements during a strong seismic event independent of the superstructure. By uncoupling the superstructure from the piers, designers sought to reduce the levels of force in the superstructure elements, aiding tremendously in reducing structural damage in the bridge

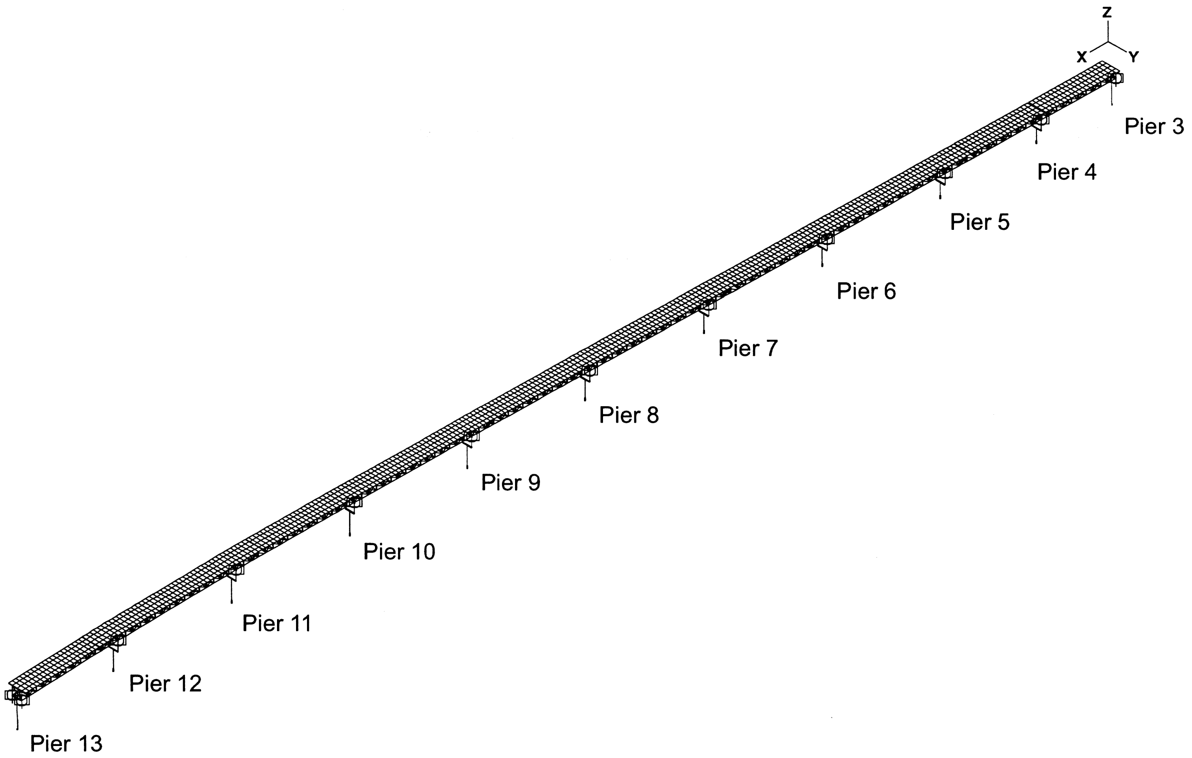


Fig. 2. Isometric view of ADINA global model.

superstructure. To affect this isolation of the superstructure, the existing rocker bearings were replaced with friction pendulum bearings implemented between the main span superstructure truss and the top of the supporting concrete piers. Twenty-two friction pendulum bearings total were designed for the main span structure, two per pier.

Additionally, the capacities of the foundations were substantially increased through the addition of caissons and enlargement of footings. The piers were also strengthened and made more ductile. Individual truss members and connections were strengthened to ensure that the main truss members remained linear throughout the earthquake loading. In particular, regions near the truss expansion hinges were strengthened.

4. Structural analysis

The ADINA finite element program was specified by the State of California for the California Toll Bridge Structure Retrofit Program, because it permits the user to evaluate important nonlinear and dynamic behavior for bridge structures.

A full nonlinear multi-support time history analysis was conducted for 20.47 s of the Green Valley maximum credible earthquake (MCE). The direct integration time history analysis was carried out for 2047 time points at a maximum time step interval of 0.01 s. The global analytical model contains approximately 4500 nodes and 16,358 degrees-of-freedom. There are over 5300 discrete members defined in 230 element groups. Figs. 2 and 3 show the global ADINA retrofit model.

The global analysis process was refined such that changes in geometry could be implemented quickly, and the model could be exercised expeditiously. Batch processes were developed and used repeatedly for each new global analysis and the associated post-processing. Similarly, the local models used to evaluate some of the retrofit sub-systems were queued such that analysis and post-processing could be completed overnight.

Throughout the project, local models were developed to study, verify and validate various modeling assumptions and procedures. Such studies were conducted for the friction pendulum bearing assemblage before implementation into the global model.

5. Description of friction pendulum bearing

The friction pendulum bearing acts to isolate the

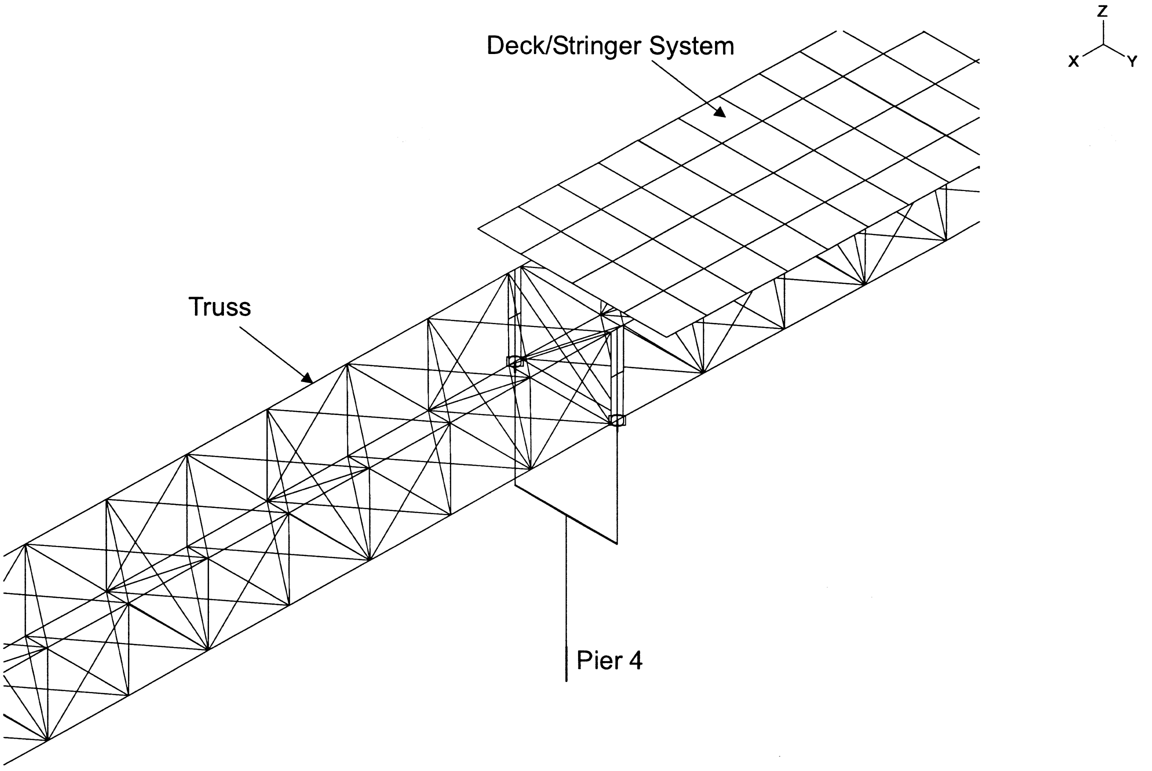


Fig. 3. Close-up isometric view of ADINA model (deck is cut away for view of main truss).

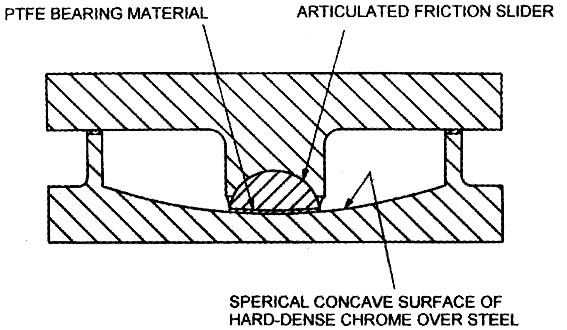


Fig. 4. Schematic of friction pendulum bearing (courtesy of Earthquake Protection Systems Inc., Emeryville, CA).

structure through its unique geometry. An articulated slider on one side of the bearing transfers normal forces to the other side of the bearing, which is a concave, spherical surface with a special liner material (Fig. 4). The liner material has known frictional coefficients, and the friction coefficient between the articulated slider and the spherical bearing surface can be varied slightly depending on the structural design requirements.

Under nonisolated periods of vibration, lateral movement is resisted through Coulomb friction forces in the bearing given by the following equation:

$$F_{\text{friction}} = \mu_s N \tag{1}$$

where μ_s is the static coefficient of friction between the articulated slider and the spherical bearing surface, and N is the normal force of the articulated slider on the bearing surface. However, when the friction force is exceeded, the slider moves and the structure responds at its isolated frequency.

Because of the spherical geometry of the bearing surface and vertical loads resulting from seismic motion, the normal force is not constant. (The equations contained herein are taken from [3] and [4].) Also, when the friction force is exceeded the lateral displacement of the bearing is resisted by a 'restoring' force, which results from the spherical geometry of the bearing surface. This tends to push the slider back toward the center of the bearing. The restoring force, is thus, highly nonlinear, given by the following equation:

$$F = \frac{N}{R}U + \mu N \,\text{sgn}\,(\dot{U}) \tag{2}$$

where N is the normal force given by Eq. (3), R is the radius of curvature of the spherical bearing surface, U is the lateral displacement, μ is the sliding (dynamic) coefficient of friction, and $\dot{U}$ is the velocity.

The normal force for a vertically rigid structure also varies as given in the following equation:

$$N = W\left(1 + \frac{\mathrm{d}N}{W} + \frac{\ddot{U}}{g}\right) \tag{3}$$

where W is the weight, dN is the additional normal force due to the spherical geometry of the bearing surface, $\ddot{U}$ is the vertical acceleration, and g is the acceleration due to gravity.

6. Friction pendulum bearing ADINA modeling and assumptions

The friction pendulum bearings were implemented in the global bridge model as a system of ADINA node-to-node frictional contact surface elements and linear springs (Fig. 5). The contact surfaces implemented were flat. Because much of the behavior of the bearings is tied directly to the geometry of the system, several assumptions concerning the restoring force were addressed to elicit a more accurate representation of the bearing behavior.

The surfaces were made arbitrarily large compared to the actual bearing surface. This was done to ensure that the lateral displacements during the earthquake did not exceed the limits of the contact surface element and cause the analysis to abort prematurely. The limits of each bearing were checked against the displacement

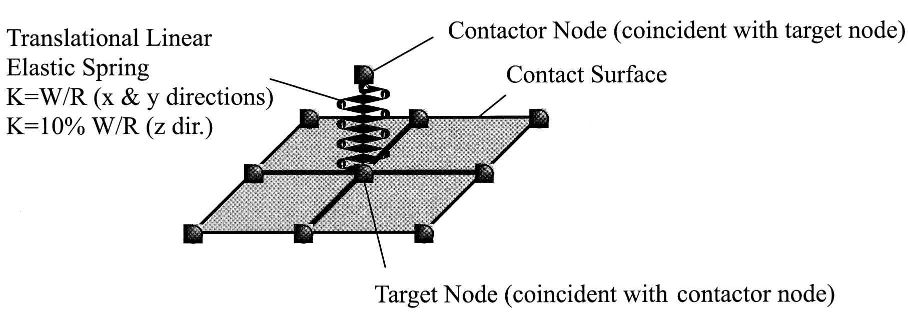


Fig. 5. Schematic of modeling of friction pendulum bearing in ADINA.

trajectories as a post-processing issue after the time history run was complete. If needed, the bearings were then re-sized according to the appropriate safety factors and maximum displacements recorded in the time history analysis. The node-to-node contact surface algorithm was invoked. The static coefficient of friction used for the contact surface elements was 6% for the final global analysis. The dynamic (velocity-dependent) coefficient of friction could not be implemented.

The target node in the bottom of the bearing and the contactor node at the top of the bearing were coincident and at the center of the contact surface. Because the frictional contact elements were flat surfaces, the lateral restoring forces associated with the spherical geometry of the bearing dish were implemented via linear springs between the target node and contactor node. Eqs. (2) and (3) were assumed to be linear per verification and testing discussed at length in [3] and [4]. The normal force (Eq. (3)) was assumed to be constant and equal to the weight of the structure on the bearing. The contributions of additional normal force from the spherical bearing surface geometry and the vertical accelerations were ignored for the normal force as they were time- and displacement-dependent variables and could not efficiently be incorporated in the normal force calculation. Eq. (2) was further linearized as the contribution of sliding friction, which was velocity-dependent, was also ignored in the calculation of the restoring force. Hence, the restoring force was a linear quantity given by the following equation:

$$F = \frac{W}{R}U \tag{4}$$

where W is the weight of the structure on the bearing, R is the radius of curvature of the spherical surface of the bearing, and U is the lateral displacement of the bearing. The stiffness of the linear springs used at each bearing in the model was, therefore, W/R. As the friction pendulum bearings implemented in the retrofit design were quite large, the radius of curvature specified for the spherical surfaces was also large leading to relatively flat bearing surfaces. The bearing geometry worked in favor of the linear restoring force stiffness and flat bearing surface assumptions.

Lastly, a ‘dummy’ linear spring was implemented between the contactor node and target node in the vertical degree of freedom (global z-direction of the model). The spring was necessary to provide numerical stability to the system. The stiffness of the spring was made small in comparison to the lateral springs, 10% of the stiffness of the lateral springs. The forces in this spring were monitored as a post-processing step to ensure that the limited tensile capacity of the bearing forces in the springs did not exceed the tolerances set for the bearings at any time during the earthquake motion.

7. Local model studies

As part of an on-going effort to verify and validate modeling issues for the global analysis model, local models were created and numerous studies were conducted to investigate assumptions and procedures, which were subsequently incorporated in the global analysis bridge model. These local studies played a very important role in the overall analysis effort. Many different issues were studied for the Benicia-Martinez Bridge. However, proper behavior of the friction pendulum bearings was a key issue for the designers and was examined in three different studies presented here.

Because adequate documentation and research had been conducted to verify the properties of the friction pendulum bearings, the assumptions outlined in the previous section regarding the linear bearing properties were thought to be adequate and usable for the global bridge model. The model was instead tested against similar models in two other finite element codes to ensure that the ADINA modeling was accurately capturing the expected behavior. The other two finite element programs were NEABS and 3D BASIS, a program developed specifically to simulate bearing behavior.

NEABS was the program used for the global design model for the Benicia-Martinez Bridge. As part of the independent design review and check process, the ADINA model was created. To help reconcile fundamental differences in the two programs, the first study conducted investigated the responses of the friction pendulum systems due to a single degree-of-freedom input using similar models. The 3D BASIS model was another convenient tool that contained a friction-based element to test and compare both the ADINA and NEABS friction elements.

The second study compared the responses of the two different systems used to model the friction pendulum bearings due to bi-directional input. The system of elements used in the ADINA study was the same as was implemented in the global analysis model (Fig. 4). The NEABS model used was slightly different and is described in Section 7.2 of this paper.

The final study was conducted to compare the responses of the friction pendulum bearings and the forces transmitted through the bearings to the surrounding structure. One pier was selected and responses were compared between ADINA and NEABS. Overall, this process of verification and validation aided enormously in substantiating and de-bugging components of the global model before enormous

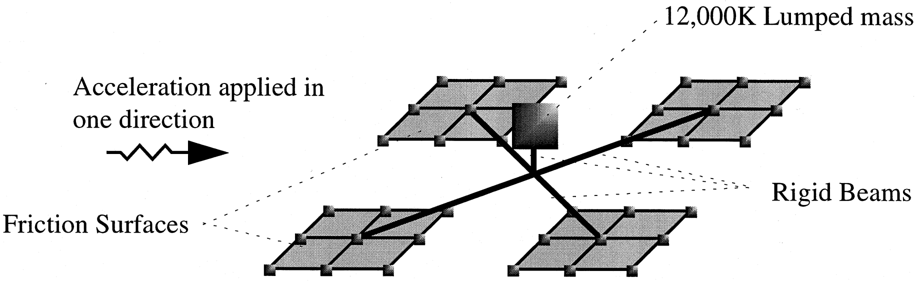


Fig. 6. Schematic of friction pendulum bearing test model.

effort and resources were expended toward trying to resolve issues within the global model.

7.1. *Uni-directional friction pendulum bearing study*

This study was conducted to compare the behavior of the elements used to model the friction pendulum bearings (FPB) in three finite element programs, ADINA, NEABS and 3D BASIS. In the study, the top of the bearing model in each analysis program was accelerated in one direction for a very simple comparison of the friction elements in each program.

The study model (Fig. 6) utilized four sets of massless, stiff spring elements connected at a central node at which a lumped mass 373 kip-s^2/ft (equivalent to 12,000 kips force) was applied. This center node was also the point of application for a global-Y acceleration time history. This model was developed to be consistent with the modeling used in the NEABS and 3D BASIS programs. The maximum displacements were as shown in Table 1.

The maximum relative displacements correlated well between ADINA, NEABS and 3D-BASIS. The ADINA maximum relative displacement was within less than 2% of the NEABS and 3D BASIS analysis results. Also, the maximum friction force matched the expected value of 300 kips (1334 kN). The displacement time history plots from all three analyses were nearly identical. The ADINA, NEABS and 3D-Basis displacement time history plots are shown in Figs. 7–9, respectively.

Based on the good correlation of results from this study between each of the finite element programs, a comparison of two different modeled systems of friction pendulum bearings could be compared using a more complex loading pattern in two different directions.

7.2. *Bi-directional friction pendulum bearing study*

This study was conducted to compare the behavior of the system of elements representing the friction pendulum bearings in ADINA to those in NEABS by exciting the bearings in two directions simultaneously. The primary point of interest of the study was to compare the effects of the NEABS friction interaction approximation, which used special frictional lateral springs in two directions, with the more generally representative frictional contact surface element and linear spring system used in ADINA.

For this study, the ADINA model, previously described and shown in Fig. 5, was defined consistent with that of a friction pendulum bearing having a radius of 120 in and a friction coefficient of 10%.

The study showed very close correlation between the NEABS and ADINA friction pendulum bearing models and helped to correlate the design and independent check global models, such that the third phase of the study could proceed as discussed in Section 7.3.

7.3. *Pier 6—friction pendulum bearing model*

This study was conducted to assess and compare the ADINA friction pendulum bearing representation to the NEABS representation, and the effects of these two models on the response of a typical pier structure. The goal was to test the friction pendulum bearing as thoroughly as possible before implementing the bearing models into the global ADINA model.

Before creating a local model of Pier 6 with the friction pendulum bearing, forces and moments at the top

Table 1
Comparison of maximum displacements

Analysis	Max. displacement
ADINA	27.70 in (704 mm)
NEABS	27.60 in (701 mm)
3D BASIS	27.30 in (693 mm)

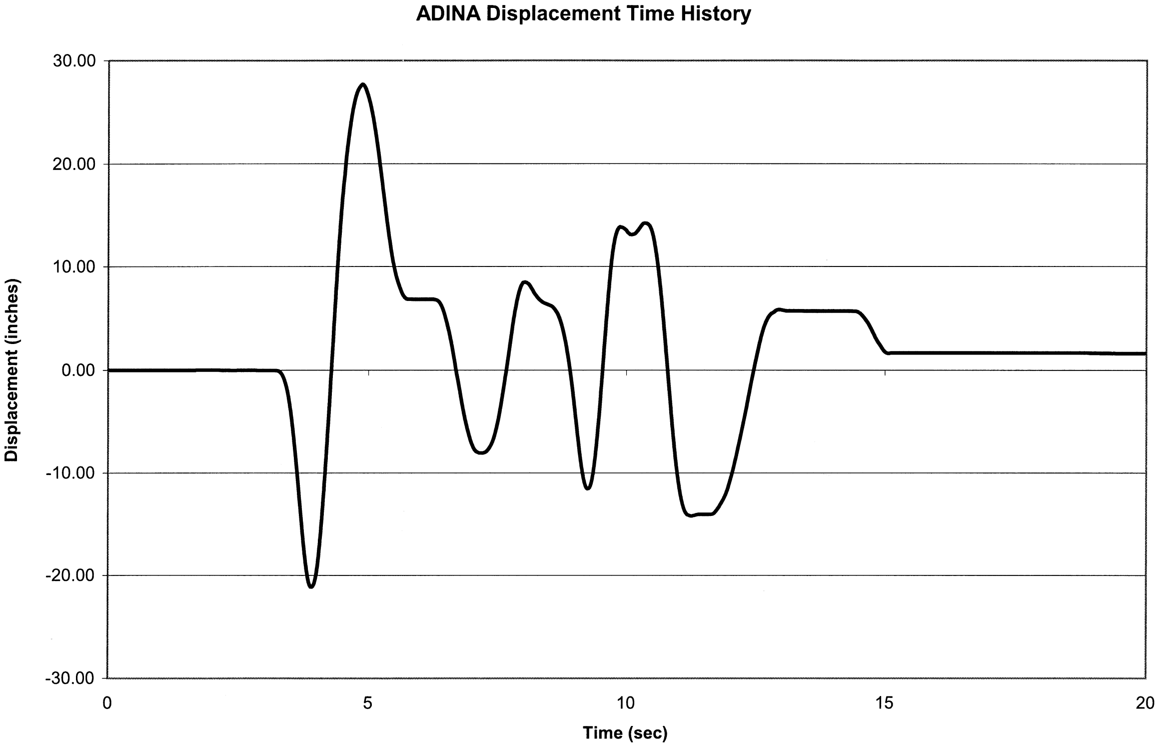


Fig. 7. ADINA displacement time history for the uni-directional study.

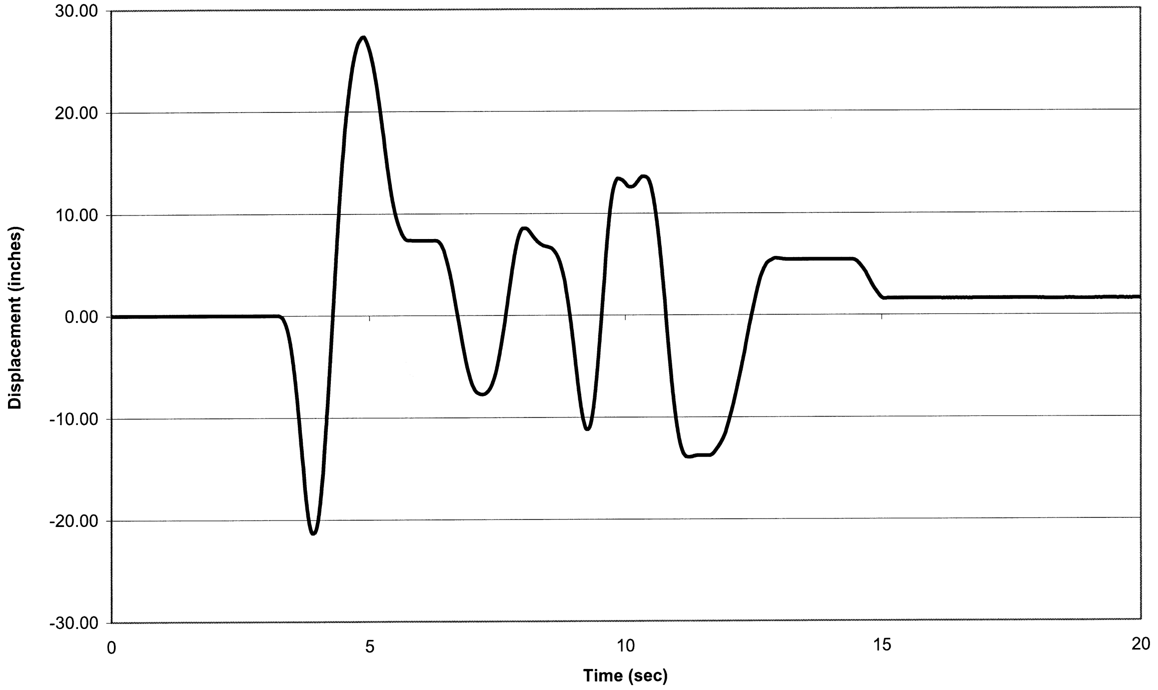


Fig. 8. NEABS displacement time history for the uni-directional study.

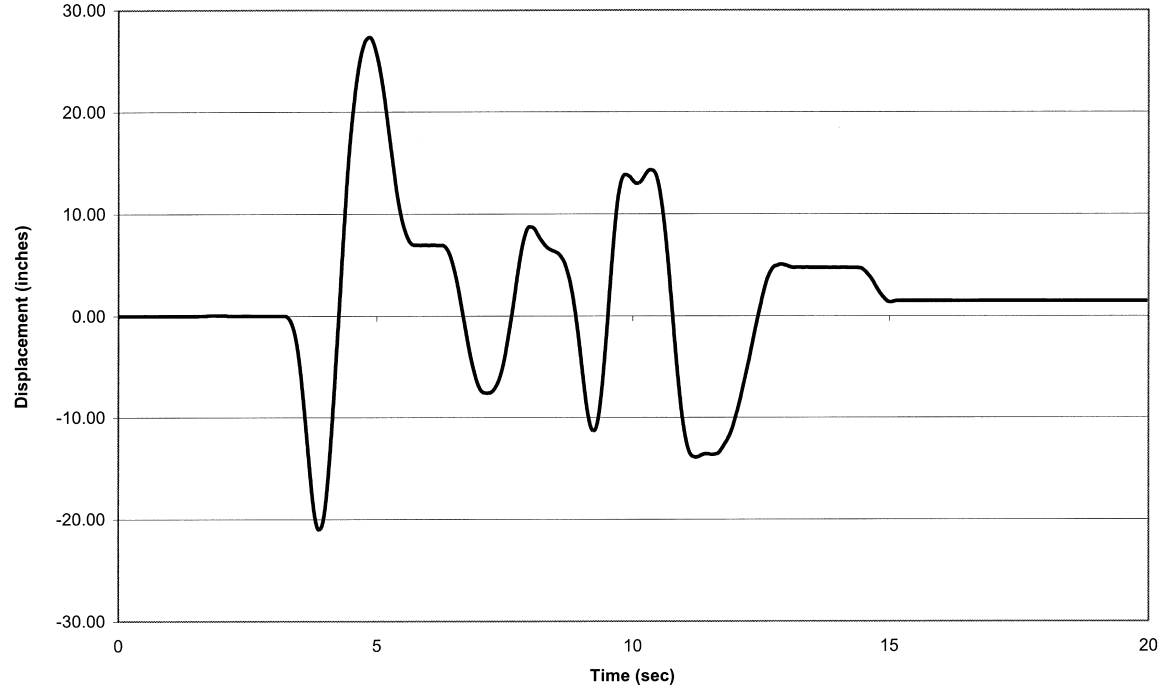
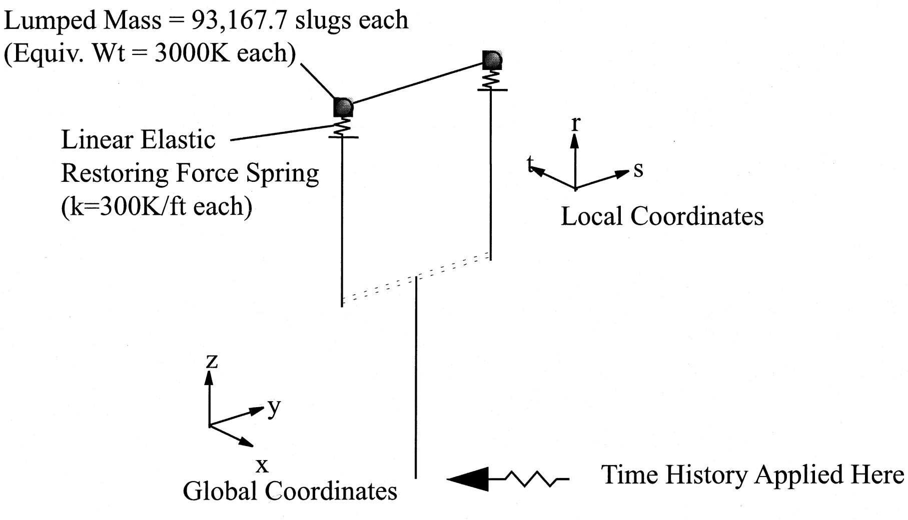


Fig. 9. 3D BASIS displacement time history for the uni-directional study.

of the columns, the top of the pier wall, and at the top of the footing from the NEABS and ADINA pier models were compared to ensure that the two models behaved similarly. This was done to ensure that any differences in behavior between the ADINA and NEABS Pier 6 models were due to the bearings. The models were adjusted until forces and moments from the two finite element programs were correlated.



Pier 6

Fig. 10. Schematic of Pier 6 model with friction pendulum bearings.

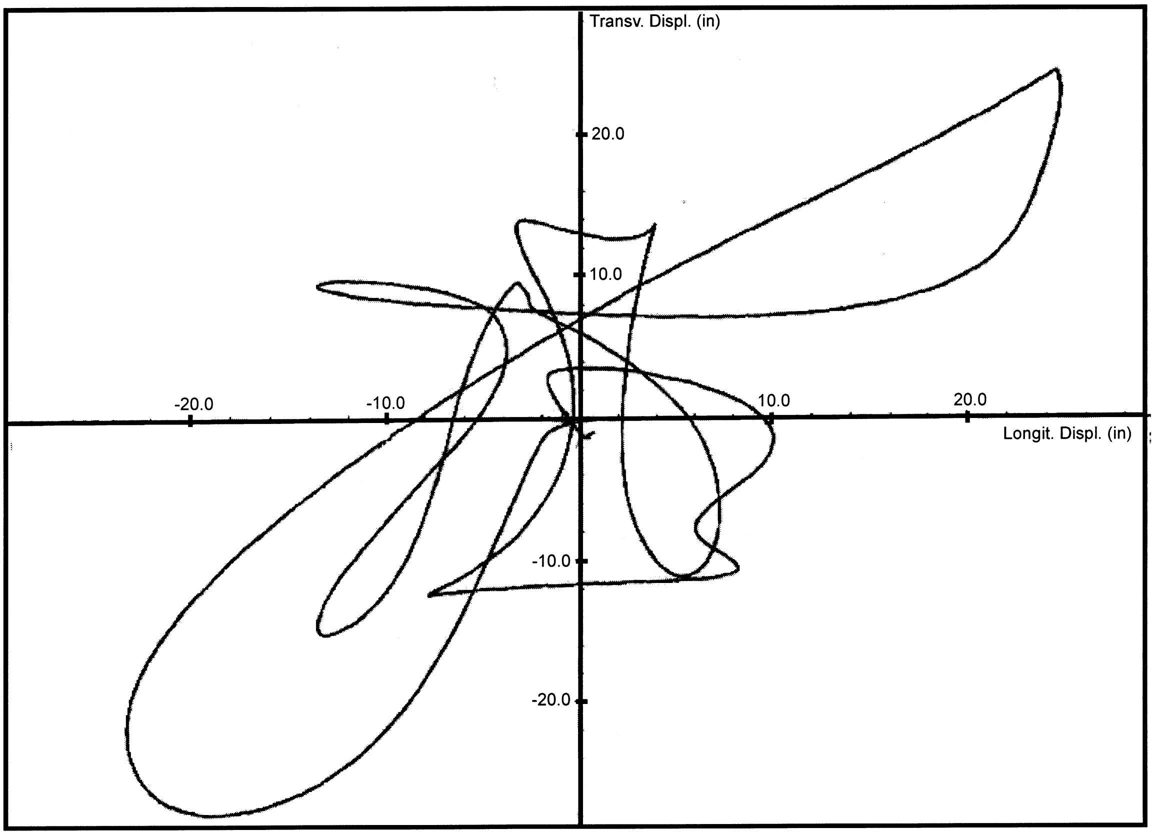


Fig. 11. ADINA friction pendulum trajectory displacement history for Pier 6 study.

Lumped masses were added to the Pier 6 model to represent the loads from the superstructure. These masses were connected to each other through a massless stiff beam and were subsequently connected to the pier by the bearing models developed in the bi-directional bearing study (Fig. 10). The displacement time histories were applied at the base.

NEABS and ADINA displacement time histories at the bearings and force and moment time histories at the tops of the columns and at the base of the pier were compared. The general shapes of the time histories matched well. The results from both models correlated reasonably well. The maximum displacements and forces predicted by the ADINA model were slightly higher than those predicted by the NEABS model. Figs. 11 and 12 show the ADINA and NEABS relative displacement trajectories at the friction pendulum bearings. This study helped the analysts identify and understand the small differences in behavior between the NEABS design basis model and the ADINA independent check model. The analysts gained confidence in the friction pendulum bearing model and its behavior and implemented the system into the global analysis bridge model.

8. Global analysis

After testing and studying the friction pendulum bearing sub-system, the elements were implemented in the global ADINA bridge model. As expected, the bearings underwent large displacements, however, forces in the superstructure were kept at acceptable levels. Displacement trajectories of the bearings were monitored throughout the time history analysis. Fig. 13 shows the displacement trajectory at Pier 9, one of the piers with the largest displacement excursions for the postulated earthquake event.

These trajectory plots were a very valuable post-processing tool. They were used immediately following the time history analyses to determine if the bearing parameters at each pier were adequate for the magnitudes

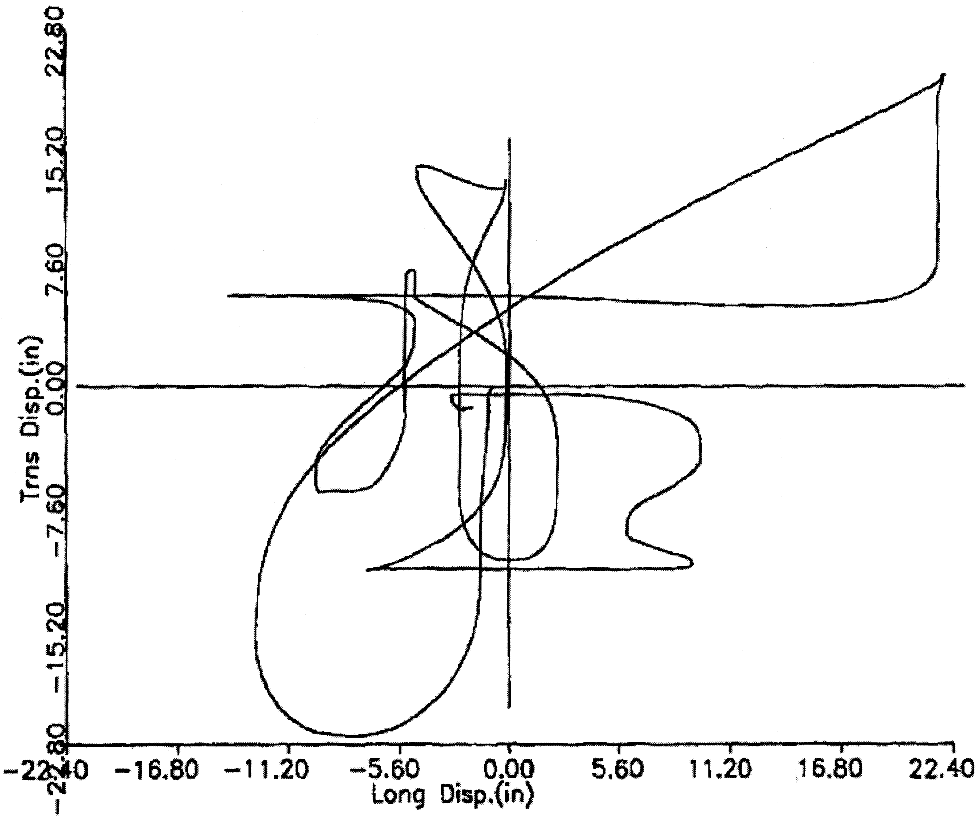


Fig. 12. NEABS friction pendulum trajectory displacement history of Pier 6 study.

of displacements exhibited in the time history analysis. For sizing the bearings at each pier, the trajectory plots were a better indicator than the transverse and longitudinal displacement time histories, because they showed the path of the bearing through the earthquake. For the final retrofit design, bearing widths ranged from 80 to 139 in and generally provided adequate margins of safety for displacement. Force time histories and friction forces in each bearing were also monitored to ensure the adequacy of the bearings.

While the testing and implementation of the friction pendulum bearings into the global model were an important aspect of the overall analysis, there were several additional key issues which required considerable testing and local modeling before implementing into the global model. A sub-structuring technique was automated and used extensively throughout the global model where complicated new retrofit geometry was implemented. This procedure aided tremendously in reducing the number of degrees of freedom from the global model system, while allowing designers to adequately evaluate new retrofit schemes for sensitive areas of the bridge. Countless studies and local models were also used to evaluate and verify foundation stiffness and parameters between the design model and the ADINA independent check model. Additionally, local models of the deck and stringer system were used to verify composite and noncomposite behavior, and to verify orthotropic material properties implemented for the shell elements representing the deck/stringer system in the global model.

Construction sequencing using element birth and death options was also implemented in the global model to obtain proper stress distributions in existing structural elements before retrofit measures were introduced. This was particularly challenging, especially in regions where the friction pendulum bearings were implemented, as at the time of production the version of ADINA which was being used to analyze the structure did not allow for element birth or death of contact surfaces. Fig. 14 shows a schematic of element birth and death used in the global analysis to implement a

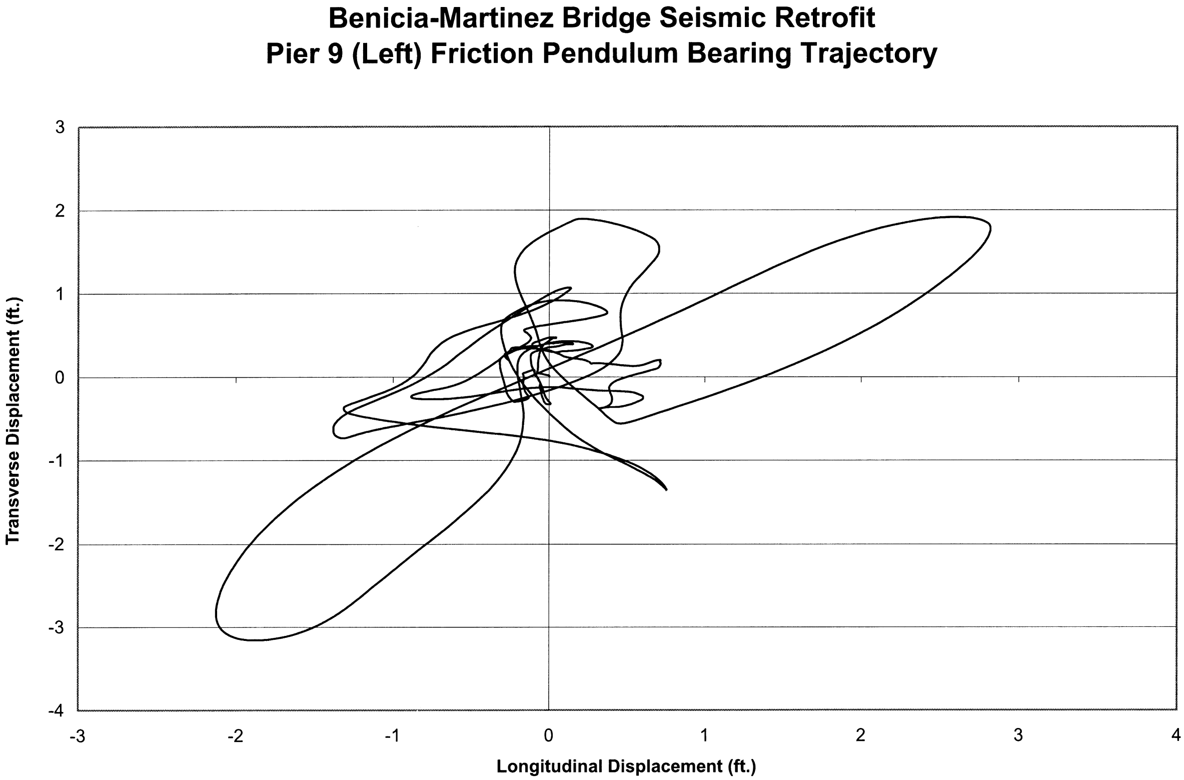


Fig. 13. Typical friction pendulum bearing displacement trajectory plot from the bridge global nonlinear time history analysis.

friction pendulum and retrofit construction sequence near Pier 4.

The final global ADINA model of the Benicia-Martinez Bridge represents over 3 years of verification, validation, and testing, all of which aided tremendously in ensuring the adequacy of the new retrofit design to meet the stringent safety standards of the State while taking advantage of new technology for large civil structures.

9. Future research and testing

While experimentation and testing have been conducted for building structures, there have been only a limited number of cases in the United States in which friction pendulum bearings have been implemented on bridges. The scale of the bearings required for a large bridge such as the Benicia-Martinez has not been implemented or fully tested to date. A rigorous full-scale test program funded by the California State Department of Transportation is scheduled to commence in the spring of 1999 at the University of California, San Diego. Fig. 15 shows an artist's rendering of the upcoming friction pendulum bearing test set-up and facilities. These tests will provide bridge designers and researchers with sorely needed experimental data from which to correlate accurate behavioral models and design safe, economical isolation systems for important transportation structures such as the Benicia-Martinez Bridge.

10. Conclusions

The use of the ADINA program was instrumental in validating the adequacy of the retrofit design of the Benicia-Martinez Bridge. The efficiency and accuracy of the global model was enhanced through the use of sub-structuring techniques and element birth and death options available in ADINA. Through the use of the frictional contact element in ADINA, the global dynamic behavior of the bridge was verified with the implementation of friction pendulum bearings at each pier. The system of elements used to represent the friction pendulum bearings was compared to those in other programs. The behavior observed was very similar, giving the design and analysis team

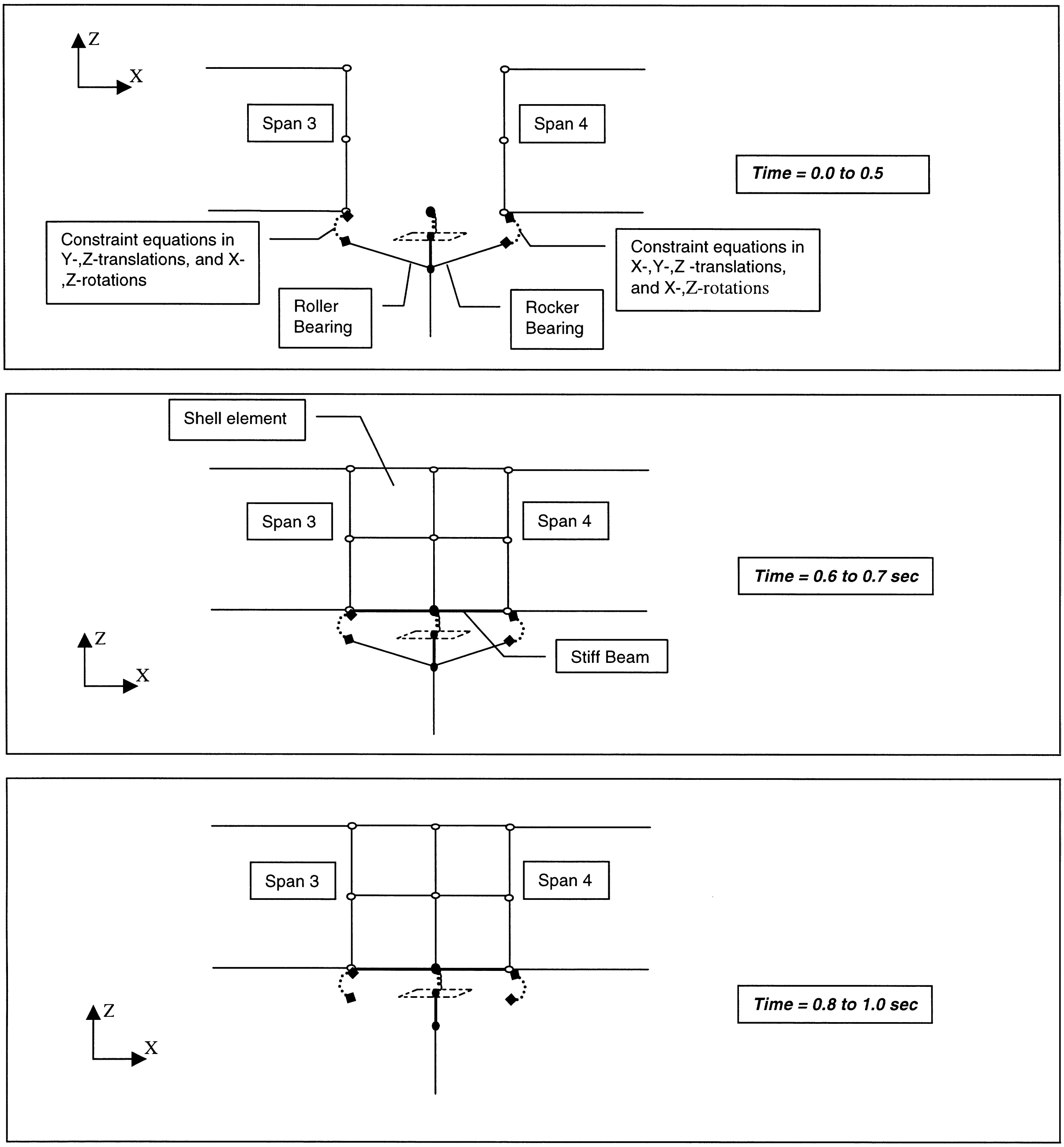


Fig. 14. Schematic of element birth/death options used to implement construction sequence of retrofit and friction pendulum bearings at Pier 4.

confidence in the modeling and proceeding to implement this system into the global analysis bridge model. While much is still unknown about using friction pendulum bearings on large bridge structures, the nonlinear time history analysis conducted on the global model of the Benicia-Martinez Bridge, coupled with new research and experimental testing, will aid structural engineers in pushing the state-of-the-art in new seismic retrofit strategies and design for large bridges.

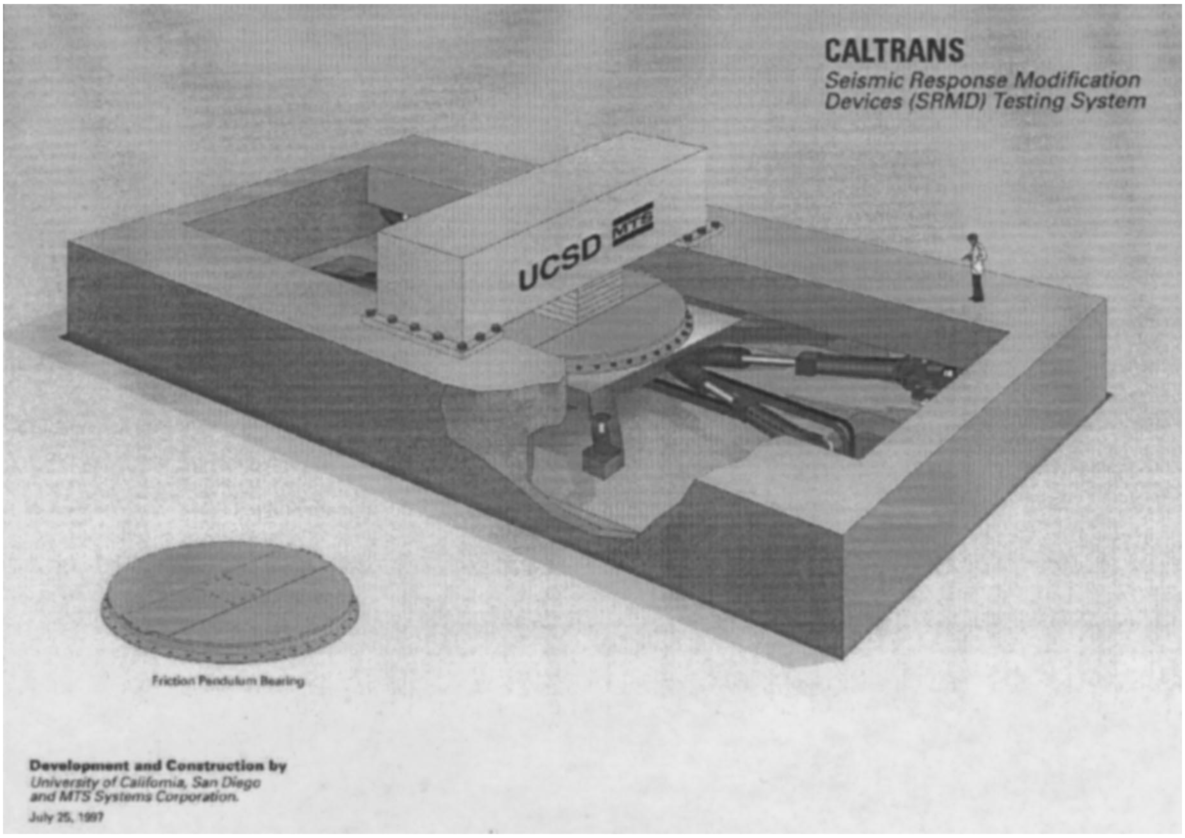


Fig. 15. UCSD friction pendulum test facility.

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