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Seismic Response of Steel Suspension Bridge

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Abstract

Performing accurate and realistic numerical simulations of the seismic response of long-span bridges presents a significant challenge to the fields of earthquake engineering and seismology. Suspension bridges in particular represent some of the largest and most important man-made structures and ensuring the seismic integrity of these mega-structures is contingent on accurate estimations of earthquake ground motions and accurate computational simulations of the structure/foundation system response. A cooperative, multi-year research project between the University of California and the Lawrence Livermore National Laboratory has recently been initiated to study engineering and seismological issues essential for simulating the response of major structures. A portion of this research project is focused on the response of long-span bridges with the San Francisco-Oakland Bay Bridge serving as a case study. This paper reports on the status of this multi-disciplinary research project with emphasis on the numerical simulation of the transient seismic response of the Bay Bridge.

1.0 Background

As a result of the 1989 Loma Prieta and 1994 Northridge California earthquakes, there has been an increased awareness about the seismic vulnerabilities of transportation systems. Many of California's most important bridges were built between the 1930's and the 1960's and they predate modern seismic analysis methodologies and modern seismic design codes and standards. Consequently, some of these bridges have numerous deficiencies which will require retrofit attention. To address the problems, the California Department of Transportation has undertaken an extensive seismic evaluation and retrofit program aimed at ensuring the seismic integrity of California's transportation system. Caltrans' funded research on the behavior of bridge structure components has provided the sound technical basis for much of the retrofit strategy development. For example, the experimental research work of Astenah-Asl and his coworkers [1] has provided understanding of the nonlinear response characteristics of steel structure components which is essential for the retrofit design of the eastern crossing of the San Francisco-Oakland Bay Bridge.

Despite these intensive efforts, much remains to be learned about the global dynamic response of large bridge systems. The characterization and effects of variable support input motions and the influence of nonlinearities in large bridge structures are two areas which are not well understood and which will require significant additional research. Investigation of these important phenomenon for long span bridges will necessarily rely on large scale numerical simulations for estimating the system transient dynamic response.

The fact that many older bridge structures have a number of structural vulnerabilities complicates the performance of adequate numerical simulations. Most types of older bridges can be expected to exhibit pervasive nonlinearity when subjected to strong earthquake ground motions, even in a retrofit configuration. In the case of suspension bridges, the shear size of the structure and the fact that there are thousands of individual structural members makes the task of accurate numerical simulation and parametric studies particularly difficult. The engineer is faced with the vexing problem of accurately capturing the overall structural response behavior on the macro level, yet having a model which can still provide accurate estimates of member forces down to the local element level. For suspension bridges subjected to strong earthquake motions, significant changes in the initial bridge geometry will result in geometric nonlinearities as the stiffness of the suspension cables and deck system change appreciably with large displacements of the structure. It may also be necessary to resolve an extraordinarily wide frequency range in suspension bridge analyses. Important modes of vibration may range from on the order of a tenth of a second period to fifteen or twenty seconds period. Consideration of long period modes may be particularly important for sites located in the fault near-field where large ground displacement pulses on the order of five seconds period appear to be a possibility. Fully three dimensional, very detailed, finite element models (i.e. each individual structural element in the bridge explicitly modeled) of these structures may be possible in the future in light of emerging parallel processing technologies. However, the computational technology for a detailed three dimensional modeling approach is currently beyond the state of the art.

The cooperative Campus-Laboratory-Collaboration (CLC) research project initiated between the University of California (UC) and the Lawrence Livermore National Laboratory (LLNL) is a multi-year project which will investigate a number of earthscience and engineering issues important in the analysis of long-span bridges. The thrust of the engineering portion of the study described herein, is the development of an efficient computational structural model which can allow accurate representation of both global and local response of suspension bridges. Towards this end, special purpose finite element software is under development which is tailored to modeling the response of suspension bridges.

2.0 Previous studies and the scope of the CLC research project

A number of research studies have provided insight on the nature of the dynamic response of suspension bridges. Abdel-Ghaffar [2,3,4] has contributed greatly to the modern understanding of suspension bridge dynamics. Abdel-Ghaffar developed detailed analytical models for suspension bridges and his work has provided fundamental information on the natural vibration characteristics of suspension bridges. His work considered the three dimensional dynamic response of suspension bridges including important coupling between directional responses. Abdel-Ghaffar employed the analytical models to determine the global free vibration characteristics of suspension bridges and the mode shapes determined from the analytical models exhibited good agreement with measured modeshapes for selected existing suspension bridges. Abdel-Ghaffar and Scanlon [5,6] also added to the state of knowledge on suspension bridges with experimental studies on dynamic bridge response. The dynamics of suspension bridges linearized about the dead load configuration were investigated with experimental observations on the Golden Gate Bridge. The authors were able to identify a large number of natural modeshapes of the bridge system and they identified modes with periods as long as eighteen seconds for the Golden Gate Bridge.

Recent studies of relevance include the consideration of the effect of spatially varying ground motion on the response of long-span bridges. Harichandran, Hawwari and Sweidan [7] employed a very simple two dimensional finite element model of the Golden Gate Bridge in an assessment of spatially varying input motions. For their study, the authors utilized the stochastic ground motion model developed by Harichandran and Vanmarcke [8] to characterize the input motions. The authors concluded that the use of identical support input motion will result in significant underestimation of some response quantities, and that the effects of multiple support motions become more acute as the bridge span increases. Nazamy and Abdel-Ghaffar [9,10] conducted computational studies on the response of long-span cable stayed bridges, including the effects of geometric nonlinearities and varying support input motion. The variable support input motions were characterized with 1979 El Centro earthquake records which were recovered from spatially varying accelerometers with common time circuits. Nazamy and Abdel-Ghaffar concluded that accounting for geometric nonlinearities is essential for long center span bridges (spans of 2000 feet and longer) and that multiple support input motions can have a significant effect and should be considered in the seismic response of long-span bridges if the response is not to be underestimated.

Detailed, three dimensional, nonlinear computational analyses of long-span suspension bridges have been performed on a very limited basis. The time intensive construction of detailed three dimensional models of these large structures does not lend itself to the scope of a typical academic research project. On the other hand, practical bridge evaluation projects are often subject to schedule constraints which preclude extensive parametric and sensitivity studies. It is intended that the current multi-year research effort will bridge the gap between these types of efforts and assist in understanding the detailed nonlinear response of long-span suspension bridges.

The multi-disciplinary CLC research project undertaken by the UC and LLNL will study many aspects of the seismic response of long-span bridges. The work will include estimation and synthesis of earthquake ground motions at a bridge site, and detailed computational simulations of transient bridge response will be performed in order to study the earthquake response of long-span structures. The western crossing of the San Francisco-Oakland Bay Bridge (see Fig. 1) was selected as a case study because this bridge, and its geologic setting, embody many of the issues which require research attention. The Bay Bridge is the critical transportation link between the city of San Francisco and the entire eastern bay area. The western crossing is currently being evaluated by the California Department of Transportation for retrofit (Ketchum and Waggoner [11] and Cooper and Reno [12]), and a corollary objective of the current study is to provide any information which might be of use to Caltrans in their retrofit of this important structure.

The Bay Bridge was constructed in the early 1930's, and the earthquake design of the structure consisted of application of a static loading equivalent to 0.1g. The bridge is situated approximately midway between the Hayward and San Andreas Faults as indicated in Fig. 1. The distance to the nearest point of the San Andreas Fault is approximately 14

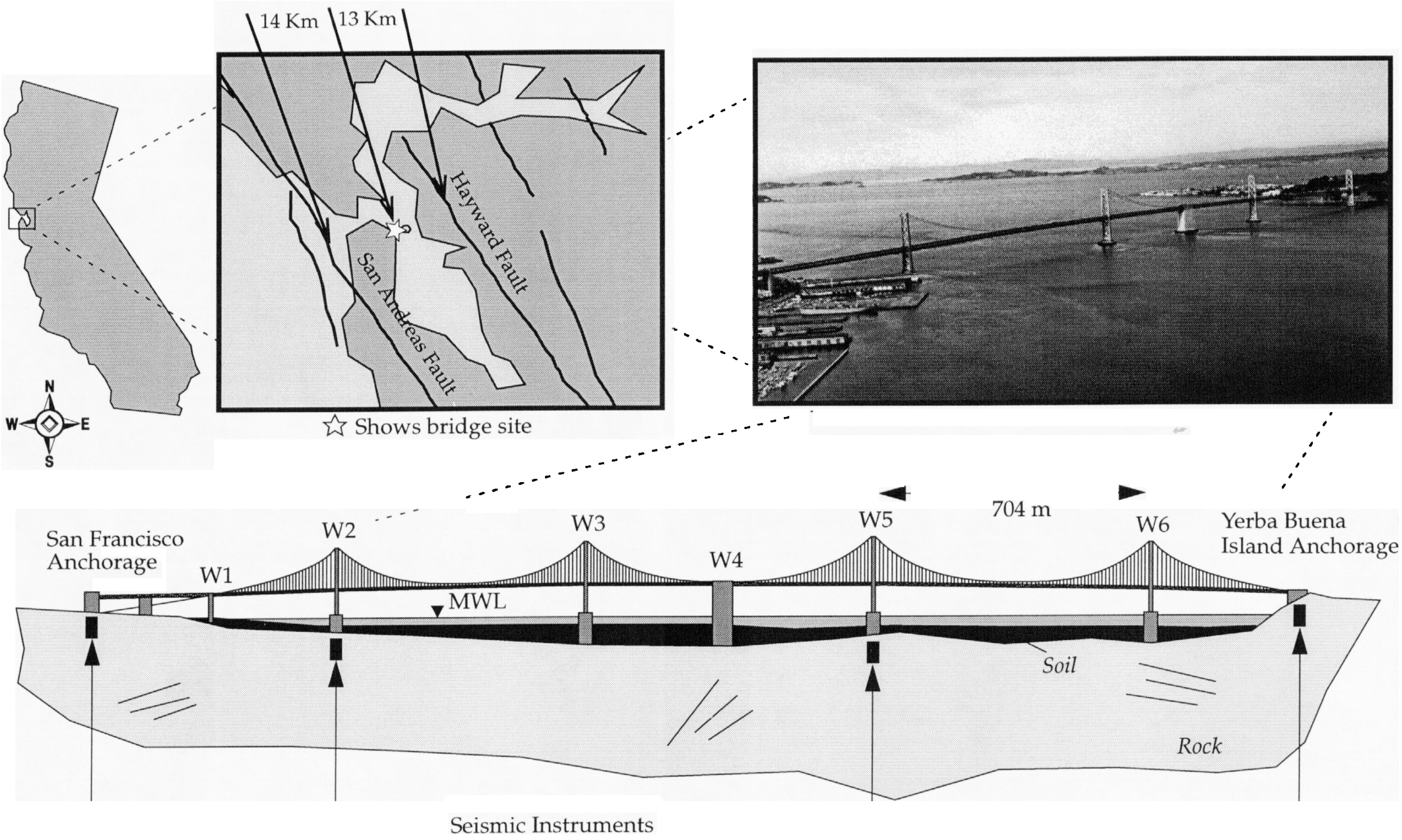

FIGURE 1. Location, geology and instrumentation plan for the western crossing of the San Francisco-Oakland Bay Bridge.

Km, while the distance to the nearest point on the Hayward Fault is about 13 Km. The most recent studies by the United States Geological Survey have estimated that a magnitude 7+ earthquake has about a 70% chance of occurring on the Hayward fault in the next thirty years, thus the likelihood of this structure being subjected to a major earthquake within its remaining life is quite high.

2.1 Ground motion estimation

Since 1989, a wealth of information has been obtained from California's strong motion instrumentation arrays. This data has shown the potential for considerable spatial variations of earthquake ground motions due to local geologic conditions and seismic wave radiation patterns (Benuska et. al. [13] and Hall et. el. [14]). New insight has also been gained into the nature of strong motions in the near field and the potential for large, long period, fault normal displacement pulses near the fault (Somerville and Graves [15]). The physical basis for the complexity of earthquake ground motions is found in the mechanics of how the earthquake fault ruptures and the manner in which seismic waves radiate through geologic material. For example, the directivity of the fault rupture propagation, i.e. whether the rupture propagates towards or away from a particular site, appears to have a major effect on felt ground motions.

For the CLC research project, a geophysics based, computational approach for synthesizing strong ground motions will be employed. The methodology developed by Hutchings and his coworkers at LLNL (Hutchings et. al. [16,17,18] and Jarpe and Kasameyer [19], McCallen and Hutchings [20]) relies on empirical Green's functions which characterize source to site wave propagation for a small patch on the causative fault. In the most simplistic terms, this procedure for generating ground motions for a large earthquake can be thought of as summing up the contributions from all of the individual patches of the fault as indicated in Fig. 2.

One of the potential advantages of this methodology is that site specific ground motion signatures are being utilized in the synthesis and thus the wave path propagation effects are being properly accounted for. This method implicitly assumes that superposition applies in the convolution process, thus the response of the geologic system is assumed to be amplitude independent and linear. This would clearly not be the case if the geologic medium through which the waves propagate consists of a soft soil. To help ensure that linearity constraints are met, the seismic instruments which measured the empirical Green's functions are placed into bedrock at the site where ground motions are estimated.

For the Bay Bridge, four advanced instrumentation packages are being placed at selected locations along the western crossing. The instruments will be located on rock outcrop at the San Francisco and Yerba Buena anchorages and in deep boreholes into bedrock at piers W2 and W5 as shown in Fig. 1. These instruments will record frequently occurring small earthquakes (i.e. M=1 to 2) continuously over an extended period of time to develop a suite of empirical Green's functions for the Hayward and San Andreas faults. The instruments will have a common time scale and thus wave passage and incoherency effects will be included in the measurements. The Green's functions will then be used to generate synthetic strong ground motions for the Bay Bridge site. This procedure, as applied to bridge analysis, is described in Hutchings and Jarpe [21].

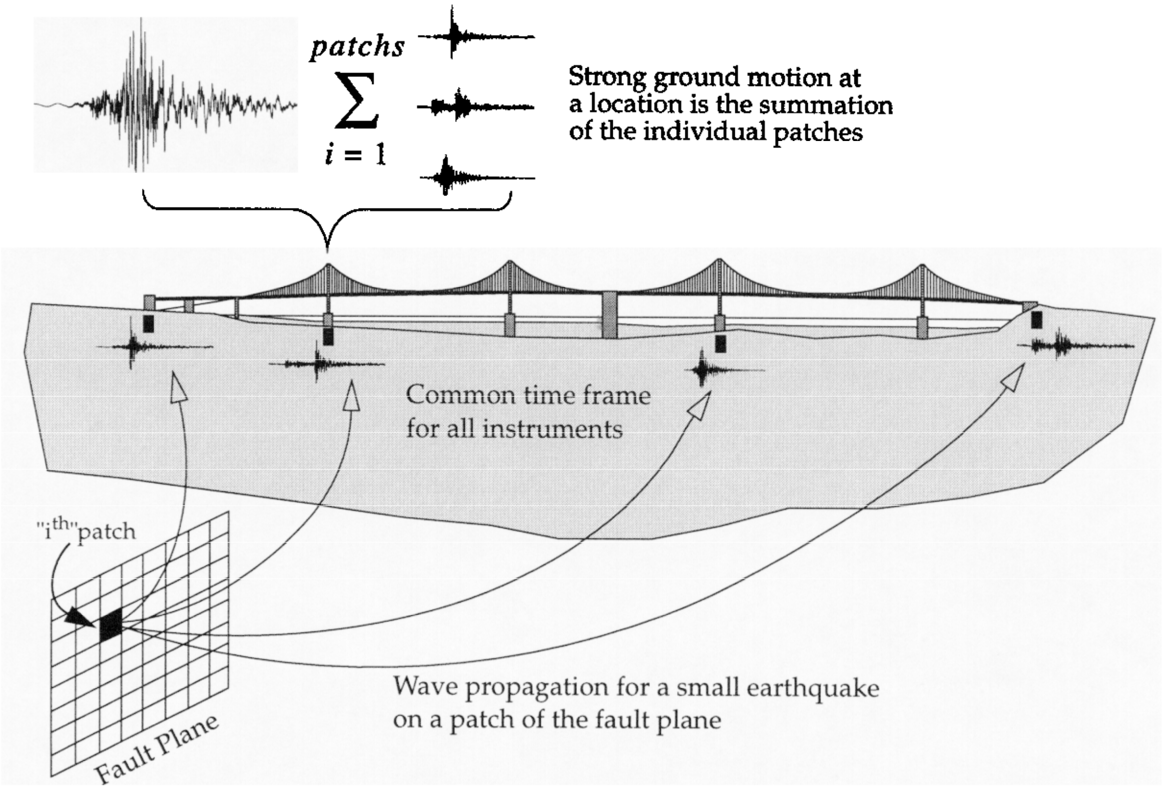

FIGURE 2. Synthesis of strong ground motion from measured empirical Green's functions.

2.2 Computational structural model

Parametric and sensitivity studies will be performed to determine the response of the bridge to the synthetic ground motions. A special purpose software tool for efficient analysis of long span bridges is under development which will be tailored to analyzing the response of suspension bridge structures (McCallen and Astaneh-Asl [22]).

Geometric nonlinearities will be considered throughout the modeling effort to account for geometric changes in the tensioned cable system and the second order interaction between large vertical cable forces and the bridge towers. Large displacements of the deck stiffening truss may also result in significant stiffness changes and the potential for geometric nonlinearities due to deck to tower impact must also be addressed. The commonality of the finite element technology developed for the SUSPNDRS program is that each element type has an element updated Lagrangian coordinate system which translates and rotates with the element to account for large rigid body motions of the elements.

The global solution architecture of the SUSPNDRS program employs an incremental, iterative nonlinear solution scheme with full Newton-Raphson or Quasi-Newton equilibrium iterations. Based on the first author's experience, Quasi-Newton procedures, in which the full system stiffness matrix is reformed only periodically upon demand, can be very efficient for the seismic analysis of long period structures where the time integration step is typically small relative to the fundamental modal periods of the structure.

2.2.1 Deck and superstructure truss model

The stiffening truss on the western span of the San Francisco-Oakland Bay Bridge consists of a two deck system without sway bracing in the transverse direction (Fig. 3a). The lack of transverse sway bracing in vertical planes significantly complicates the creation of an efficient structural model because flexural effects in the superstructure truss system lead to primary rather than secondary stresses. One option would be to model each main structural component with flexural elements and the roadway surface with shell elements, with a resulting six degrees of freedom at each nodal location as indicated in Fig. 3b. This approach would be robust, but computationally excessive if applied to a global bridge model. An alternate approach has been developed, which employs geometrically nonlinear axial force truss elements for the stiffening truss members, a geometrically nonlinear membrane element for the deck slab and a special geometrically nonlinear sway stiffness element to represent the transverse bending due to frame action in the transverse direction. The components of this deck model are shown in Fig. 3c. By design, each of these structural elements contains three translational degrees of freedom per node with no active rotational degrees of freedom. The immediate advantage of this superstructure model is a significant reduction in the global degrees of freedom. However, this discretization still allows for determination of the axial forces in the individual truss members and by post processing the sway stiffness element deformations, the moments in the deck beams and truss posts can be estimated.

This form of reduced order model was found to accurately capture the deck system dynamics and a comparison of the natural modeshapes for a reduced order model and a detailed model of a ten bay segment of deck is shown in Fig. 4 This ten bay segment contains short wavelengths and concentrated supports relative to the full suspended deck system of the western crossing and thus represents somewhat of a worst-case test.

2.2.2 Bridge tower model

The towers of the suspension part of the Bay Bridge consist of cellular steel plate construction. The ideal discretization of the towers would be accomplished with a large scale model of nonlinear shell elements. This representation would be prohibitive in a global model however. For the SUSPNDRS program, a finite displacement, finite rotation fiber beam element has been developed for representing the cellular structure of the Bay Bridge towers. This element, the details of which are found in McCallen and Astaneh-Asl [22], employs three cartesian coordinate systems for each flexural element as shown in Fig. 5. Two nodal corotational coordinate systems rotate and translate with the principal axes of the element at each node point (the x''-y''-z'' and x'''-y'''-z''' coordinates in Fig. 5) and an element updated coordinate system translates with the element longitudinal axis (the x'-y'-z' system in Fig. 5). The cross section of the element is divided into a number of finite fibers as indicated in Fig. 5 and elastic or classical elasto-plastic material laws can be used to define the uniaxial stress-strain behavior of the material at each finite fiber. In the global solution scheme it is assumed that the element incremental nodal rotations over any given time step are small and can therefore be transformed with linear vector transformations. This assumption is appropriate for typical civil engineering applications where the individual elements are not generally undergoing extreme displacements over a given time step. Based on this assumption, the incremental global rotations can be translated to the element nodal coordinates through simple linear vector transformations and summed into the total rotation quantities.

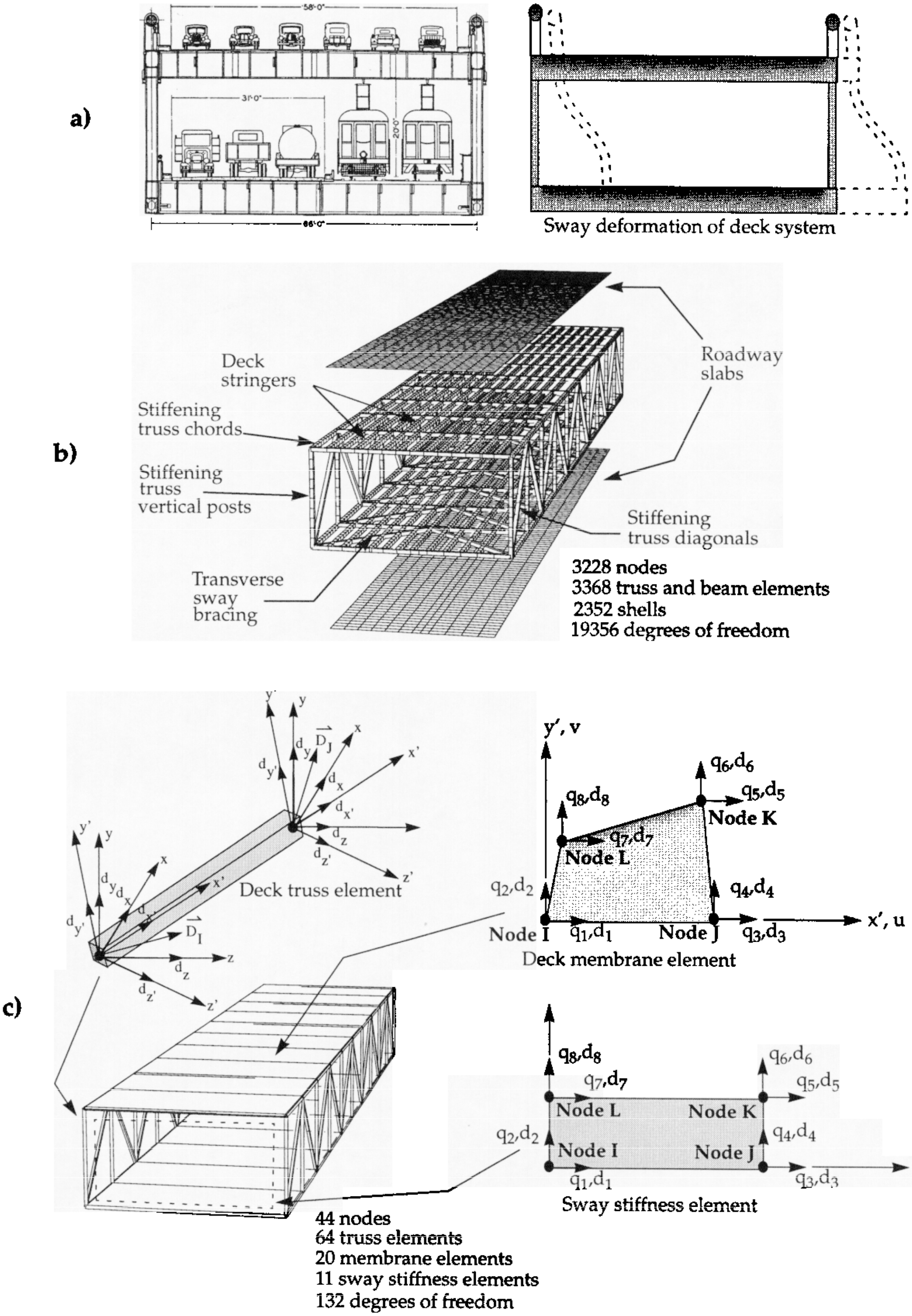

FIGURE 3. Bay Bridge deck models. a) Double deck configuration of the western crossing of the Bay Bridge; b) detailed deck model: c) reduced order deck model.

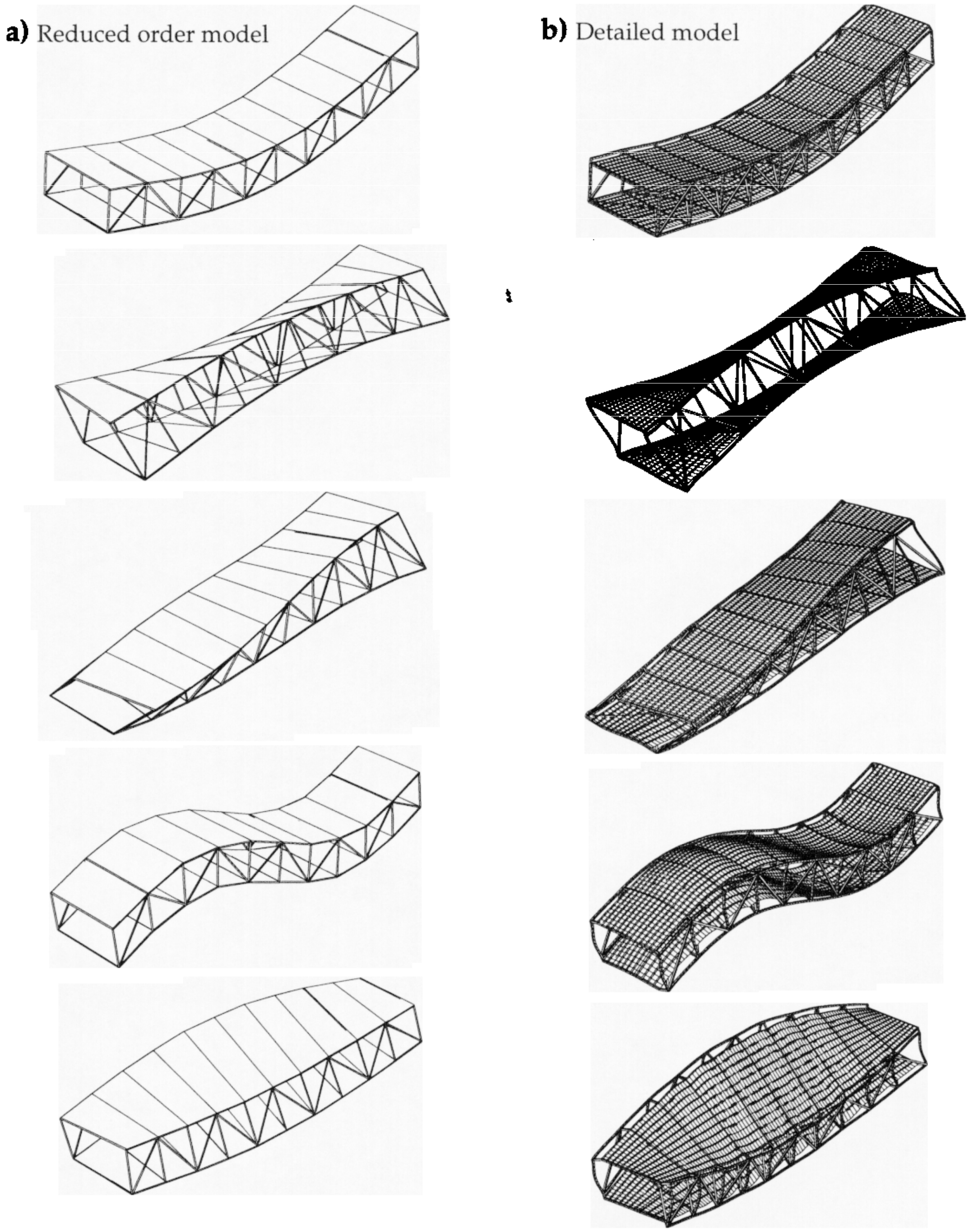

FIGURE 4. First five natural modes of a ten bay deck segment. a) Reduced order model; b) detailed model.

The fiber beam element employs three point Lobatto integration along the element length. The Lobatto integration utilizes integration points at the two ends of the element, which allows capture of plasticity at the extreme ends of the element.

The performance of the fiber element for finite deformation and finite rotations is illustrated in Fig. 5 where a simple linear elastic frame structure is subjected to transverse loading which bends it to extreme displacements. The displacements of the frame, as computed with the finite fiber element and with the independent general purpose nonlinear finite element program NIKE3D, are compared in Fig. 5. The SUSPNDRS fiber element exhibits excellent agreement with the NIKE3D solution.

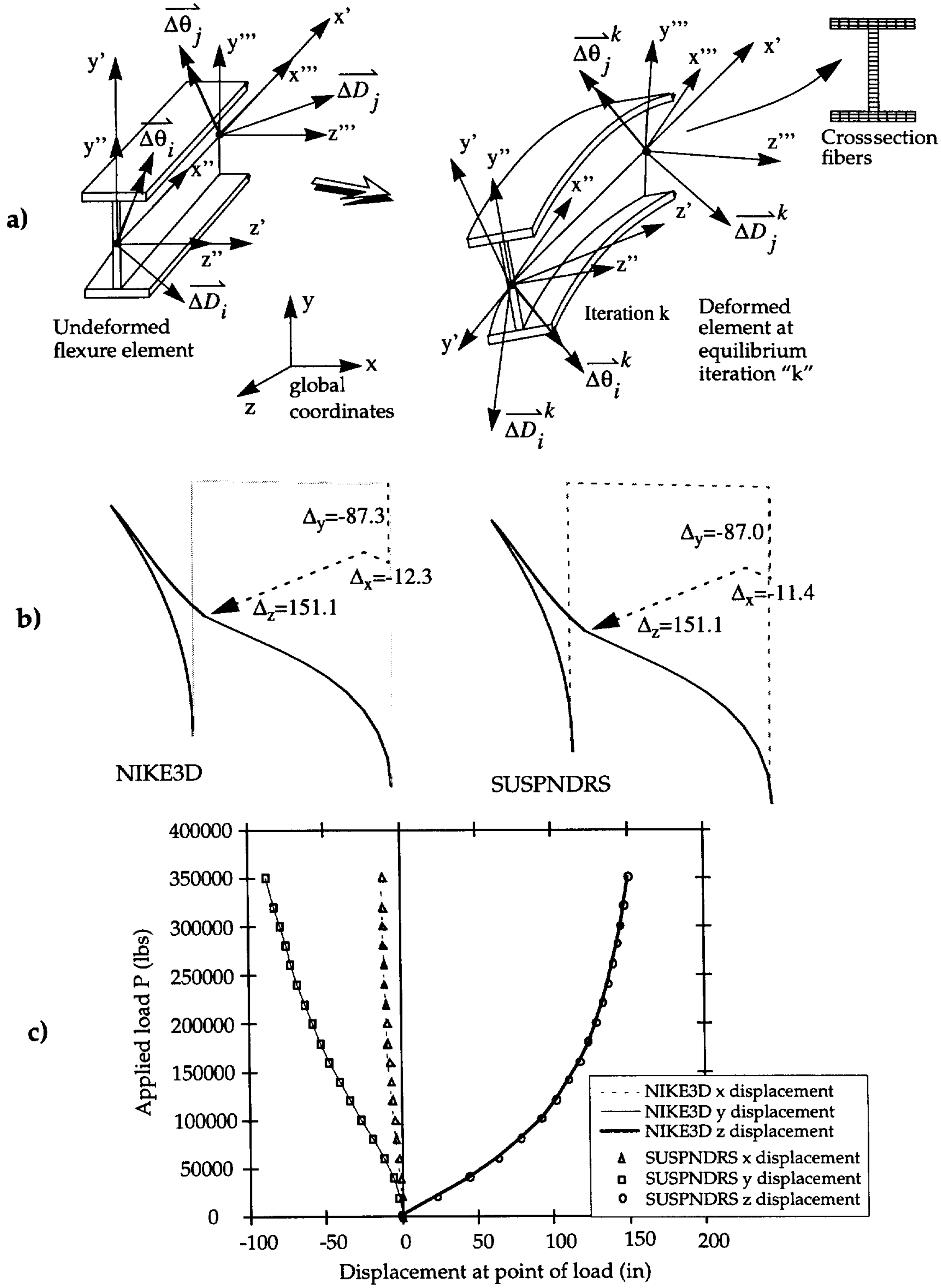

FIGURE 5. Finite displacement, finite rotation fiber beam element. a) Three element coordinate systems; b) portal frame with large displacement and rotations; c) comparison of NIKE3D and SUSPNDRS solutions.

A second example, which illustrates the ability of the finite fiber element to capture plasticity in a beam segment, is shown in Fig. 6. This problem consists of a column subjected to a transverse load at the top. The load is increased until yielding migrates across the cross section at the base of the column, and a plastic hinge is formed. For this problem the finite fiber element was compared to an elasto-plastic shell element model constructed for the NIKE3D program. As indicated in Fig. 6, the fiber element accurately captures the evolution of the plasticity and the ultimate strength of the column.

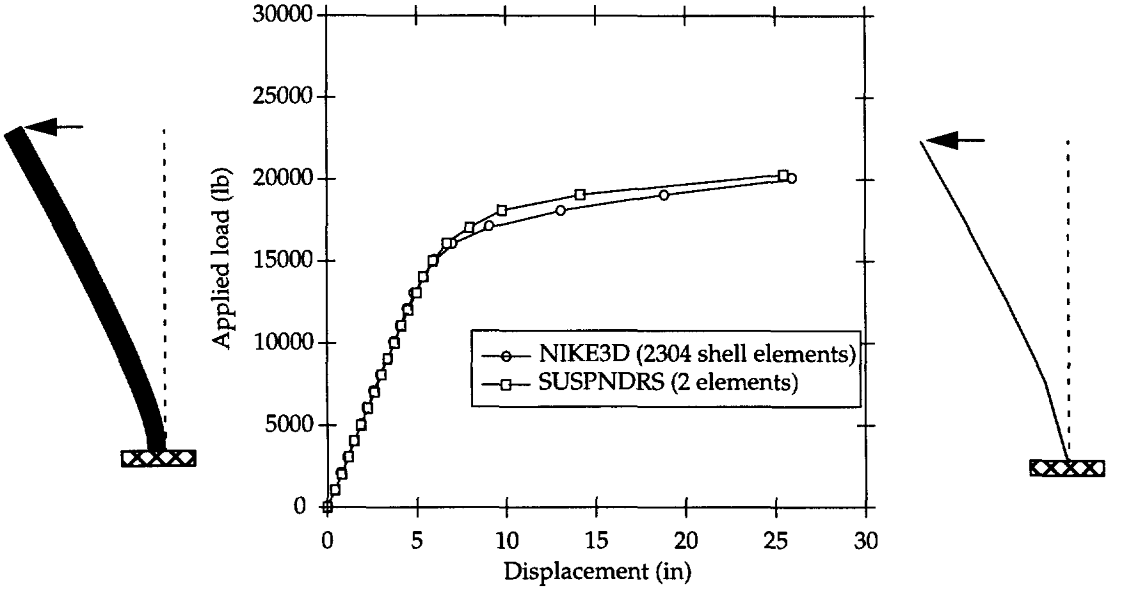

FIGURE 6. Elasto-plastic response of aW14x176 wide flange section, comparison of shell and fiber beam models.

2.2.3 Cable system model

The main suspension cable and vertical suspenders will be represented with a geometrically nonlinear, tension-only axial force element. Prior to transient dynamic analyses, the suspension bridge structure must be brought to the appropriate dead load configuration. The initial tension field in the suspension system, which through the element geometric stiffnesses essentially defines the initial tangent stiffness of the structure under dead load, will be estimated from analytical solutions and input to the structural model in the model generation process. The objective is to get as close as possible to the final deadload configuration prior to commencing equilibrium iterations. When subjected to full vertical gravity loading, the configuration of the model must achieve the appropriate deck structure geometry and the appropriate force levels in the cable system and deck truss members. This may require consideration of the actual construction sequence of the deck system in which the main span truss was segmentally lifted from the center of the span towards the towers.

3.0 Summary

A three year research project has been initiated between the University of California and the Lawrence Livermore National Laboratory. This project will address seismology and engineering issues critical to understanding the earthquake response of long-span bridges. The west bay crossing of the San Francisco-Oakland Bay Bridge will serve as a case study, and key elements of the project include synthesis of site dependent, spatially varying ground motions and nonlinear response simulations of the bridge system dynamic response.

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