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Seismic studies of the San Francisco-Oakland Bay bridge

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ABSTRACT: During the October 17, 1989 Loma Prieta earthquake, the San Francisco-Oakland Bay bridge sustained some damage and was closed for a month. Following the earthquake, a comprehensive research project has been underway at the University of California at Berkeley to study seismic behavior of the bridge and to formulate retrofit design recomendations. The study includes seismological, geotechnical and structural aspects. By developing realistic models of the bridge and subjecting the models to realistic ground motions, seismic deficiencies are being identified. This paper summarizes the progress of this study.

1 INTRODUCTION

The magnitude 7.1 Loma Prieta earthquake occurred on October 17, 1989 in Northern California causing damage throughout the greater San Francisco Bay area. The San Francisco- Oakland Bay bridge, shown in Figures 1 and 2 is located about 80 km north of the epicenter. The bridge sustained some seismic damage resulting in two 50-foot segments of the upper and lower decks of the bridge to drop off their support. The damage resulted in one fatality and 13 injuries and closure of the bridge for a month. Figure 3 shows summary of the damage which was mainly concentrated on the east side of the bridge.

Following the Loma Prieta earthquake, the Governor of California formed a board of inquiry to investigate the damage to the transportation facilities owned by the state. The Board in its report (Theal, 1990) among other items, recommended that comprehensive seismic studies of major bridges in California be undertaken. The research project that is summarized here (Astaneh et al, 1994) is an effort to conduct such an in-depth study of seismic behavior of the East Bay Crossing of the San Francisco- Oakland Bay Bridge.

2 THE SAN FRANCISCO OAKLAND BAY BRIDGE

The San Francisco-Oakland Bay Bridge is a 13.4 km long structure connecting cities of San Francisco and Oakland. The bridge was constructed during 1933-1937 period. Currently it carries about 250,000 commuters daily. The main structure of the steel bridge is shown in Figures 1 and 2. The West Bay Crossing of the bridge, Figure 1, consists of two suspension bridges placed in tandem. All piers as well as anchorages of the West Bay Crossing are supported on the bedrock. The East Bay Crossing, shown in Figure 2, consists of eighteen 88m span trusses, a 738m long cantilever truss and five 155m span trusses. There are eight expansion joints in the East Bay Crossing that divide the super-structure into ten

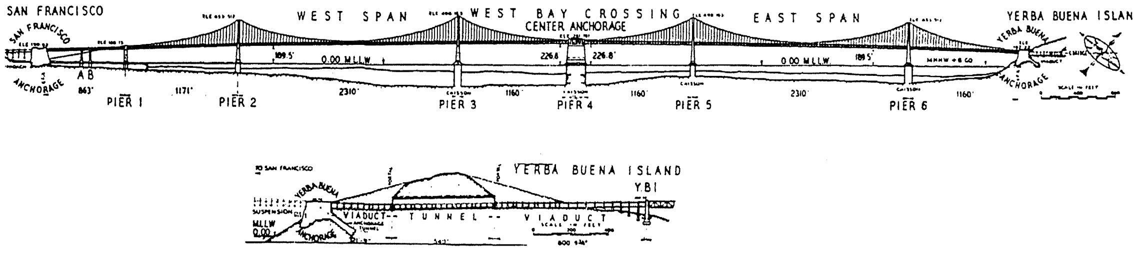


Figure 1. West Bay crossing of the San Francisco-Oakland Bay Bridge

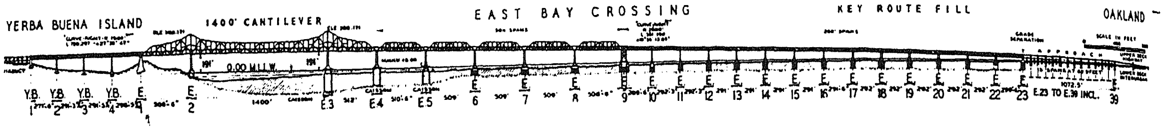


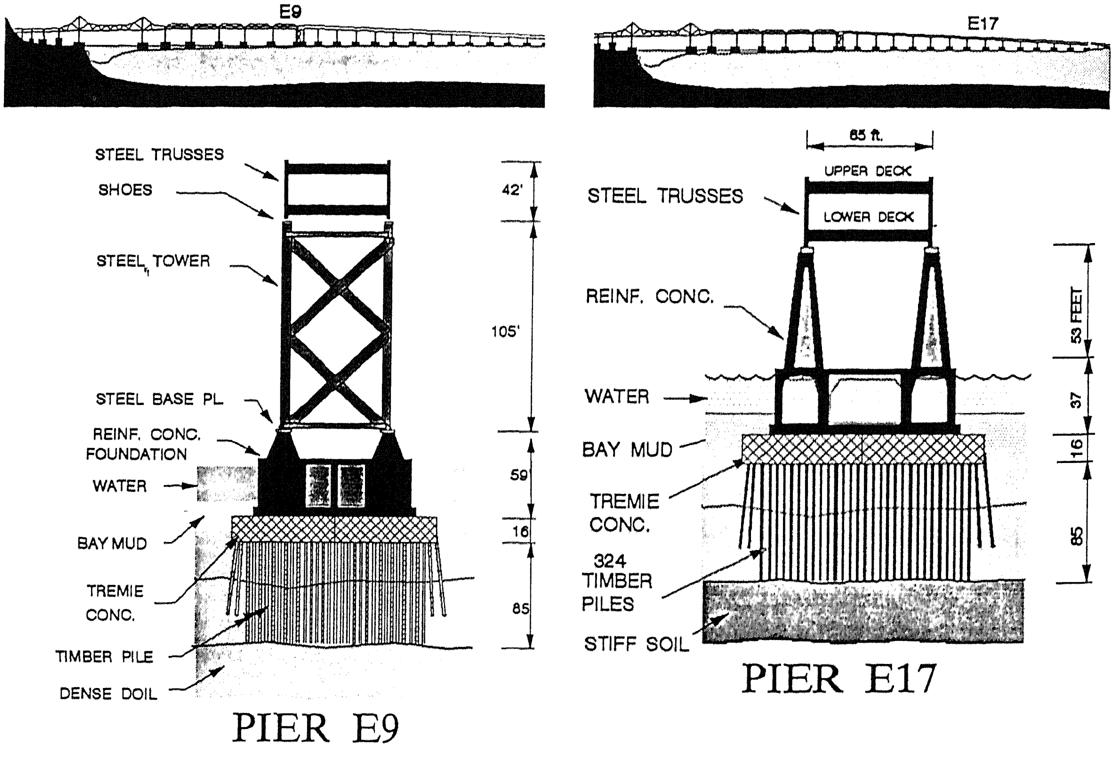
Figure 2. East Bay crossing of the San Francisco-Oakland Bay Bridge

segments. The expansion joints are at the location of Piers YB2, E4, E11 and E17 through E22. On the East Bay Crossing, Piers YB1, YB4, E1, and E2 are supported on the bedrock and all other piers are supported on the caissons or reinforced concrete hollow foundations and several hundred douglas fir timber piles. A typical structure of the concrete piers is shown in Figure 3 and some details of the typical cross section of the bridge is provided in Figure 4.

3 SUMMARY OF DAMAGE DUE TO 1989 LOMA-PRIETA EARTHQUAKE

Following the earthquake, the damage was documented and reported (Astaneh, 1989). Figure 5 shows a summary of the damage to the East Bay Crossing of the bridge. During the October 17, 1989 earthquake, fourteen trusses at the eastern end of the bridge had moved in the longitudinal direction of the bridge and caused structural damage and the collapse of two 17m long segments of the decks at the location of Pier E9. During the 1989 earthquake, the two 88m span trusses immediately to the east of Pier E9 appeared to have moved primarily in an east-west direction relative to Pier E9. The main damage in this area was shear failure of forty 25mm diameter bolts connecting shoes of the trusses to the top of the steel towers. The maximum movement of shoes was estimated to have been more than 18 cm. After the quake, a residual movement of about 13 cm in longitudinal direction eastward and about 4.5 cm in transverse direction northward were measured. Due to this movement, the stringers supporting the 15m long segments of the upper and lower decks over Pier E9 came off their seat supports and collapsed.

Another area of damage was the segment of the bridge between Piers E11 and E17. The structure of the bridge between Pier E11 and E17 consists of six 88m span trusses



PIER E9

PIER E17

Figure 3. Typical Structures of the East Bay crossing

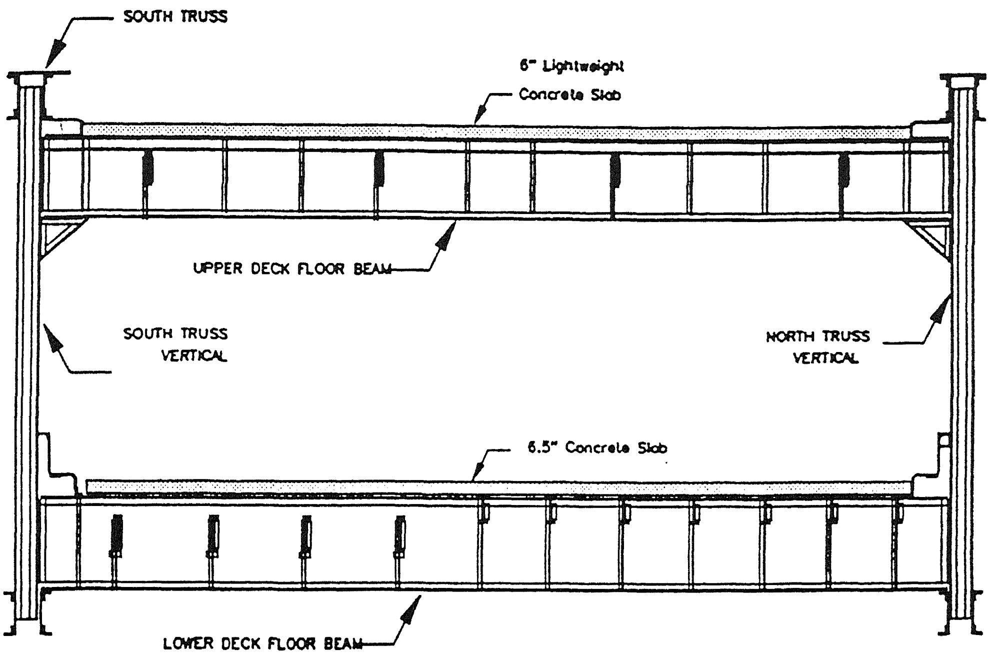


Figure 4. Typical cross section of the bridge

supported on steel columns with the exception of Pier E17 which is a hollow reinforced concrete pedestal as shown in Figure 3. During the earthquake, apparently these six spans had moved together in the east-west direction about 13 cm. causing the concrete pedestals at Pier E17 to rock about their base. The rocking caused some damage to the concrete at the base of the pedestals.

The damage in the spans east of Pier E17 was failure of a number of 25mm diameter bolts connecting the truss shoes to the top of the piers. The shear failure of these bolts had resulted in release of the trusses allowing the trusses between Pier 17 and Pier 22 to move in the east-west direction along the length of the bridge.

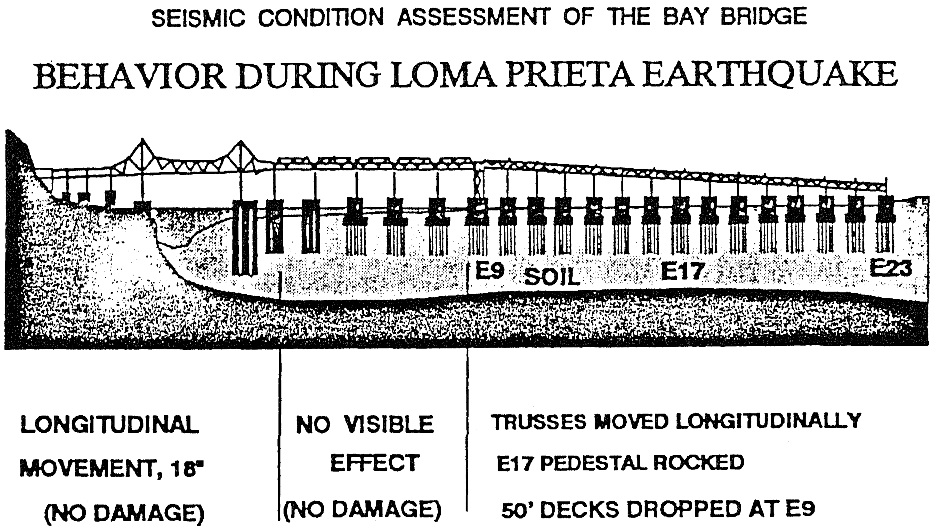


Figure 5. Summary of the damage

4 SEISMIC STUDIES OF THE BAY BRIDGE

4.1 General

In the aftermath of the Loma Prieta earthquake, a research project was sponsored by the California Department of Transportation at the University of California at Berkeley to study seismic condition of the East Bay Crossing of the Bay Bridge and to develop recommendations for the retrofit. The main objective of the research project is to use the most advanced science and technology available, or to develop new scientific methods or technology if necessary, to evaluate the seismic behavior of the bridge during future maximum credible earthquakes that can occur at the nearby faults.

The methodology used in the project is shown in Figure 6 which can be summarized as follows. First, by studying the character of the nearby San Andreas and Hayward faults a series of ground motions are established at the likely hypocenters. Then by using information available on the seismological and geological characteristics of the ground, between the fault and the Bridge, bedrock acceleration time histories at a number of point beneath the bridge are established.

By using the bedrock motions and conducting dynamic analyses of the response of the soil to the bedrock motions, a series of free field ground motions are established at the site. Then by conducting soil-structure interaction studies, the free field motion is modified to include the effects of the presence of the piles, foundations and the structure. The last stage is to built a realistic computer model of the superstructure, subject the model to base excitations developed in previous stages and conduct a series of time history dynamic analyses. The process is iterated as many times as necessary until a refined and realistic model of the behavior of the bridge emerges.

Two of the challenging problems facing us at this time are slippage of soil and dynamic analyses of such a large and unprecedented model. There are three layers of soil under the bridge and these three layers can slip on each other during a moderate or strong earthquake. The slippage of the soil could be beneficial in acting as a large base isolator. However, it can also harm the piers. Although because of relatively soft soil surrounding the timber piles it is unlikely that in this case timber piles can actually shear off. The subject is currently under study by the research team.

The second issue that has developed into a very complex activity is the development of new technology for modeling and conducting three dimensional inelastic dynamic analysis of the bridge. The main part of the initial research plan was to conduct a series of realistic three- dimensional non-linear dynamic analysis. However, as the building of the structural model progressed, the structure turned out to be much more complex than a typical bridge. The complexities result from from the lack of a consistent load path for seismic forces, which require a very detailed model.

4.2 Various phases of research project

The research projects has several major inter-related areas of emphasis. These are

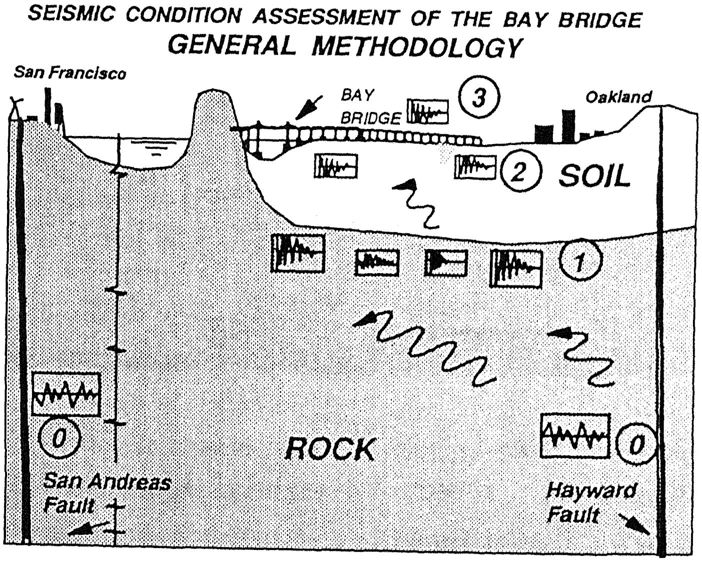


Figure 6. Research methodology

seismological aspects, geotechnical aspects, strong motion instrumentation plans, three dimensional inelastic dynamic analysis, two-dimensional inelastic dynamic analysis, three-dimensional elastic finite element analysis of components, data base management, seismic behavior, performance and limit states of various components, evaluation of seismic deficiencies and finally development of retrofit design recommendations.

In the following, more information on the progress of the project to date are provided.

4.3 Seismological aspects

The research related to seismological studies is led by B. Bolt. Work to date has indicated that for such a large, multi-supported, critical structure the seismological details of the expected ground motion are likely to be of great importance. There is an indication that the usual procedures of supplying one or two time histories and equivalent response spectra based on realistic maximum earthquake scenarios must be modified and extended.

The procedures to estimate the ground motions have developed in two different ways, mainly empirically with inclusion of incoherence along the bridge spans, and using numerical source and wave propagation models. The latter are necessary to allow matching realistic inputs into models developed for dynamic analyses of soil. The synthetic strong ground motions must be folded into the results of the soil-structure interaction computations and the dynamic analysis. This process must be thoroughly interactive and iterations made as necessary for the various critical ground motion parameters.

4.4. Strong motion instrumentation plans

The research related to instrumentation of the Bay Bridge is led by A. Astaneh. The

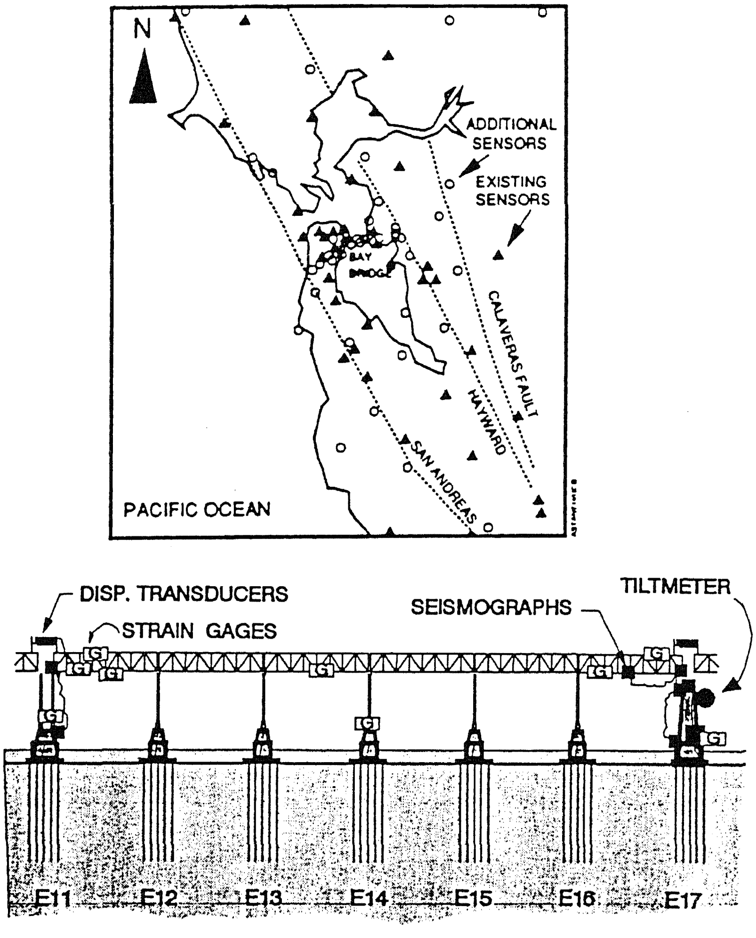


Figure 7. Proposed strong motion array for the Bay Bridge

instrumentation includes a dense array for the bridge and a network of instrumentation for the greater Bay Area. Figure 7 shows the proposed "Strong Motion Array for the Bay Bridge" (BBSMA) along with a sample of strong motion instrumentation for a segment of the Bay Bridge.

4.5 Geotechnical issues

This effort is led by J. Lysmer. The geotechnical studies have indicated that should a strong, but plausible, earthquake occur on the Hayward or the San Andreas fault, a horizontal failure plane may develop over most of the East Bay Crossing site at a depth of about 20m below the mud-line. This plane passes through the pile groups on which the majority of the piers of the bridge are founded. Currently no method exists for analyzing this problem. A major effort has been embarked upon to develop new methods which can (1) determine whether or not the pile groups can survive or prevent the postulated failure and, (2) produce pier motions and other parameters needed for a seismic analysis of the bridge for extreme seismic events.

Since the foundations of eastern part of the bridge are also deficient, currently several retrofit concepts are being investigated to retrofit the foundations and to protect timber piles. The challenging issue is to devise a retrofit system that will be activated during a major earthquake but will not change structural character of the initial design of the bridge.

4.6. Dynamic analysis

The main activity regarding dynamic analysis of the Bridge is to develop a realistic three dimensional, inelastic model of the entire structure and subject the model to realistic ground motions. The effort is led by G. Powell. The Bay Bridge has a very complex structural system.

In order to conduct dynamic analysis of models of this size, condensation techniques should be used aggressively to reduce the number of degrees of freedom to a few thousand. This has required the research team to develop new computational techniques and computer programs.

In addition to above-mentioned 3-D inelastic analyses, a series of 2-D inelastic and 3-D elastic analyses of the system are also being considered. This effort led by A. Astaneh is intended to establish global and local behavior by using more common structural analysis software.

4.7. Data base management

This effort is led by G. Fenves. The large number of nonlinear earthquake analyses of the Bay Bridge models generate an enormous amount of response data. A computer database was designed and implemented specifically for providing an engineering evaluation of the earthquake response of the bridge. The database includes all the information about the models (elements, nodes, etc.), static loads, ground motion analysis runs, nodal response, and components and the limit states that are to be evaluated with the capacities and the demands computed from the analyses.

4.8 Seismic condition assessment

This effort is led by A. Astaneh.

In order to ecvaluate seismic condition of the Bay Bridge, the following equation is

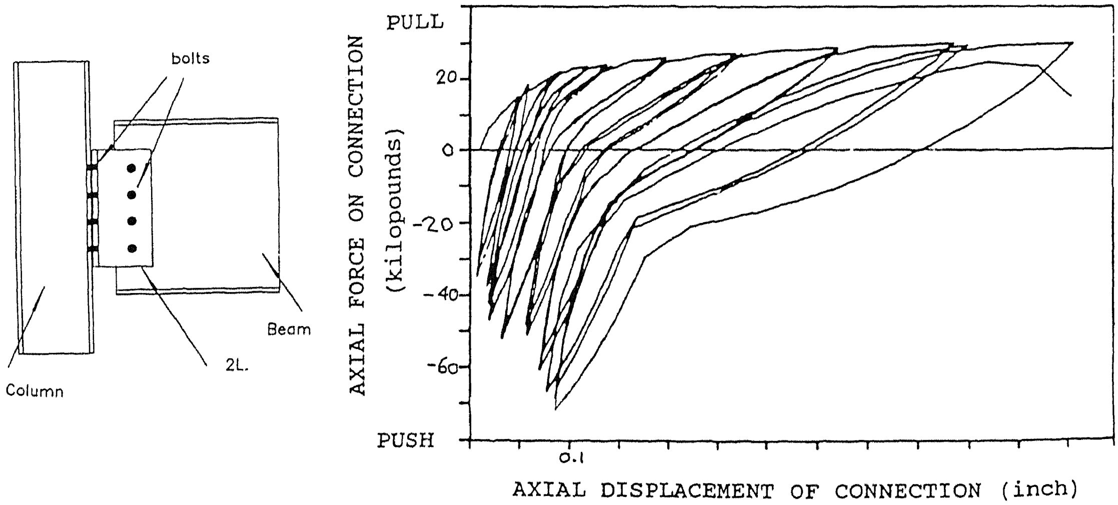


Figure 8. Behavior of angle connections subjected to cyclic axial load

applied to each limit state of components as well as systems of the Bay Bridge.

$$\text{Demand/Supply} \leq I \qquad (1)$$

The demand term in the equation results from dynamic analyses. The supply term is established for each limit state by studying seismic behavior of the corresponding component and or by conducting actual tests.

The term I in the above equation is an "Importance Factor" and is introduced to represent the importance of each limit state and consequences of reaching that limit state. In current design codes, for seismic design new structures, all limt states, related to member performance , are assigned the same importance. Even though a margin of safety is built into all codes, this margin of safety is due to uncertainties in load, material properties, geometry, workmanship, modeling and computational techniques. However, in evaluating seismic performance of an existing structure, the author believes an importance factor should be assigned to each limit state based on the past performance of the component and the consequences of the occurrence of the limit state.

This philosophy of assigning Importance Factor to limit states is being implemented in seismic evaluation of the Bay Bridge. The value of "I" in equation (1) can be less than 1.0 for secondary members of the bridge, while for important members such as truss chords "I" can be as high as 1.25.

5. BEHAVIOR OF COMPONENTS

Unfortunately, the information on seismic behavior of components of steel bridges is very limited and almost non-existent. A major effort is underway to establish actual cyclic behavior of components of the Bay Bridge by conducting tests on various components and analyzing the available test data. As an example, behavior of one of the most important connections of the Bay Bridge is summarized in the following.

As shown in Figure 4, the concrete deck of the Bridge is supported on longitudinal stringers which in turn are supported by double angle connections to the web of floor plate girders. Investigation of behavior of deck system indicated that the double angle connections can experience considerable yielding due to axial push-pull when bridge moves in longitudinal direction. To study cyclic behavior of these connections comprehensive experimental and analytical studies are underway. A total of 14 test of full scale connections have been tested under simulated cyclic loading.

Figure 8 shows a typical connection and its response to the cyclic axial load. When connections were pulled, they behaved in a very flexible manner due to bending flexibility of outstanding legs of angles. When angles were pushed against the support, they exhibited very large stiffness due to the axial stiffness of the outstanding legs bearing against the support. After sufficient number of inelastic push-pull cycles, during which the shear was maintained at a constant level, the strength of outstanding legs had deteriorated so much that the connections failed due to gravity shear. This finding has extremely important design and retrofit implications. It means that connections that are designed to carry gravity shear, usually with a factor of safety of about 2.0, during severe and long duration earthquakes, can deteriorate sufficiently such that either during the quake or afterward, the connection fails under service load alone.

In addition, due to considerable cyclic inelasticity of these connections, it is necessary to model these connections as non-linear elements in the computer model and conduct the dynamic analysis of the system.

6 CONCLUSIONS

Since studies on seismic condition assessment of the Bay Bridge (6) are still ongoing, the final conclusions are not formulated yet. However, the findings of the research reported here can be summarized as:

1. Due to the very critical role of this bridge in transportation network in Northern California, the seismic performance criterion for the Bay Bridge is set at a very stringent level. The performance criteria implemented currently is that these structure should be able to survive the maximum credible earthquakes without any structural damage that will impair its full function.
2. The studies conducted so far indicate that the foundations of the eastern part of the bridge may require extensive retrofit.
3. The super-structure appears to be in better condition than the sub-structure. However, retrofit systems will be also required for the steel super-structures.
4. The main philosophy in retrofit of the Bay Bridge is try to avoid strengthening and stiffening if possible. Instead, the efforts are directed to redistribution of stiffnesses, implementing energy dissipating devices as well as additional dampers. These retrofit strategies can result in global reduction of the forces in the system which means reduction of "demand" term in Equation (1).
4. Extensive program of instrumentation is being developed.
5. The findings of this study should be considered tentative at this time.

7 ACKNOWLEDGMENTS

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