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Golden Gate Bridge seismic retrofit project: A reference for approaching the seismic aspects of the Gibraltar Strait bridge

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ABSTRACT: The Golden Gate Bridge has served for over fifty years as a vital transportation link and key component of the only highway artery connecting San Francisco with the area to the north. The suspension bridge is considered to be one of the United State's greatest construction achievements. It is owned and operated by the Golden Gate Bridge Highway and Transportation District (District).

Immediately after the Loma Prieta earthquake in Northern California on October 17, 1989, the District engaged T.Y. Lin International (TYLI) to perform a seismic evaluation of the bridge. That evaluation completed in November 1990, determined that an earthquake on a nearby fault could cause severe damage to the bridge which could require significant repairs. The District thereupon commissioned evaluation studies of seismic retrofit alternatives.

These studies completed in July, 1991, concluded that seismic retrofitting of the Bridge is necessary and feasible for the Bridge to survive a major earthquake of a magnitude 8.25, centered on the San Andreas fault.

The District selected TYLI to prepare construction drawings, specifications and tender documents for the Seismic Retrofit of the suspension bridge. Design work is scheduled to start in October, 1992, with the first construction contracts projected to start in late 1994. Retrofit construction is scheduled for completion in 1997 at an estimated cost of $125,000,000. This will be the first seismic retrofitting of a major suspension bridge in a highly active seismic area.

Some lessons and techniques learned during these seismic studies of the Bridge that can be applied to the proposed Gibraltar Strait crossing and other suspension bridges include the need to consider in the analysis the following aspects: 1) large displacement effects, 2) multiple support excitation, 3) dynamic characteristics, 4) material nonlinearity and, 5) displacement compatibility and support conditions.

1. INTRODUCTION

The Golden Gate Bridge has served the Northern Bay Area transportation needs since 1937. At the time of its design and construction in the 1930s, it set new standards for the engineering of long-span bridges and today it is one of the most famous landmark bridges in the world.

The bridge is owned, operated and maintained by the Golden Gate Bridge, Highway and Transportation District as a toll facility. The structure has provided excellent service over its more than half-century history because the District has recognized the importance of maintaining the bridge's structural integrity. The need for maintenance and upgrading of the bridge continues as new challenges to its integrity such as seismic vulnerability are discovered.

The seismic risk to bridges was brought to the attention of the public by the October, 1989, *Loma Prieta* earthquake. For fifteen seconds, the San Francisco Bay Area was shaken by this earthquake, measured at magnitude 7.1, and centered about 130km south of the bridge site. Although the Golden Gate Bridge was not damaged by this earthquake, the San Francisco-Oakland Bay Bridge remained closed for one month during repairs for earthquake damage.

Immediately following the earthquake, the District engaged TYLI to perform a seismic evaluation of the bridge. Subconsultants Imbsen & Associates, Inc. and Geospectra, Inc. were engaged to add their expertise to the TYLI team.

The results of the seismic evaluation were presented in *The Golden Gate Bridge Seismic Evaluation*[1] in November, 1990. The evaluation revealed that a major earthquake on a nearby segment of the San Andreas or Hayward Faults would likely cause severe damage to the bridge and could cause interruption of traffic and require significant repairs. It was also concluded that structural retrofitting of the bridge was required to minimize the potential damage from a major earthquake and eliminate the need for long-term loss of service and closure of the bridge for repairs after such an earthquake.

The District then commissioned TYLI including subconsultants Imbsen & Associates, Inc. and Geospectra, Inc., to perform engineering studies to evaluate feasible means of upgrading the bridge to the level of seismic resistance, that would enable the bridge to be serviceable after a major earthquake. The studies included development and evaluation of retrofitting measures, as well as estimation of their construction costs and schedules, are presented in *Golden Gate Bridge Seismic Retrofit Studies*[2] in July, 1991.

2. BRIDGE DESCRIPTION

The Golden Gate Bridge was designed and built using the most advanced structural technology of the time. Until 1964, the bridge had the longest span of any structure in the world. Today it is considered to be one of the most significant construction achievements of its period and is recognized around the world as a symbol of San Francisco. The design and construction of the Bridge is well documented in the Chief Engineers final report[3].

The understanding of earthquake ground motions and their effects on structures has increased tremendously in the intervening years since its construction. The structural analysis theories that were used in the design of the bridge allowed a reasonably accurate evaluation of stresses and deflections under static dead load and traffic loads. They did not, however, accurately predict the response of the bridge to dynamic loads such as wind and earthquake. Wind and seismic effects were not well understood then. For example, the bridge was designed for a seismic loading of only 5% of its weight. Only recently have analytical techniques become available to accurately calculate the dynamic responses of this type of bridge to the wind and seismic forces to which the bridge could be subjected.

The 2790 m overall length of the Golden Gate Bridge consists of a number of different structure types, as shown in Figure 1. The bridge's major components are the approach viaducts, the steel arch, the cable anchorage housings, and the main suspension bridge. The approach viaducts are of steel girder and truss construction; the anchorages, anchorage housings, pylons and piers of the main suspension bridge are reinforced concrete; and the superstructure and towers of the suspension bridge and arch span are steel. The original concrete deck of the suspension bridge was replaced in 1985 with a lightweight orthotropic steel deck with a net reduction in weight of about 10,000 tonnes.

This paper discusses the seismic studies for the suspension bridge portion of the crossing.

3. SUSPENSION BRIDGE

The main structure across the strait consists of three suspended spans, a centre span of 1280 m and two side spans of 343 m. These spans are suspended from two continuous 92 cm diameter steel wire cables spaced 27.44 m apart. The cables are in turn supported on two steel towers and are anchored in concrete anchorage blocks at their extreme ends. At the shoreward end of each side spans, the cables pass through reinforced concrete pylons where they are restrained by steel cable tie-downs. The tie-downs are designed to hold the cables at a fixed support at the roadway level.

The cable anchorages are 2210 m apart, located inside reinforced concrete anchorage housings. In its current configuration, the drape of the main span cables is about 143 m.

The towers, which rise 227.44 m above low water level, consist primarily of tall slender steel shafts of multicellular steel plate construction, tapered in steps from bottom to top. At the tops of the towers, the cables are secured to the shafts by means of cast steel saddles. Above the roadway the shafts are braced together with struts in a portal configuration. Below the roadway they are braced with double cross bracing. At their bases, the tower shafts are anchored with dowels and riveted angles to the reinforced concrete piers. The tower anchors were provided only for construction phase. For the completed bridge, the towers depend on the cable restraint and weight to anchor the towers. Piers are founded directly on the underlying rock.

The suspended structure consists of two parallel 7.7- m-deep stiffening trusses, spaced 27.44 m apart with each truss located in plane with the cables. The trusses are connected to each other with a top lateral wind bracing system which was part of the original construction. A bottom lateral bracing system was installed in the 1950's, after the bridge suffered damage from heavy winds. That addition created a trussed-tube configuration to resist wind-induced torsion.

The upper deck consists of a six-lane, 19-m-wide

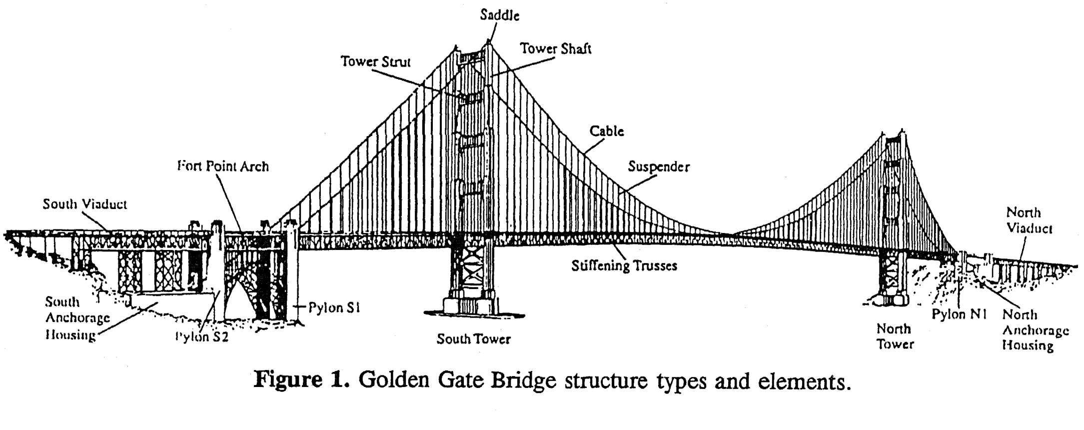

Figure 1. Golden Gate Bridge structure types and elements.

highway deck flanked on both sides by 3m sidewalks. The side spans are fixed to the towers with joints that allow only rotation about vertical and transverse axes. The main span is fixed to the tower similarly, but with a limited amount of free longitudinal movement also allowed. At the pylons, the ends of the side spans are also free to move longitudinally.

4. SCOPE OF THE STUDIES AND GENERAL METHODOLOGY

The purposes of the studies reported here were first to identify vulnerable areas of the various structures that comprise the Golden Gate Bridge. Second, to develop retrofit measures for these various structures and to evaluate the effectiveness of each of the alternatives in order to select one for further study, and then to prepare concept drawings and a preliminary cost estimate of the retrofit scheme. This work was required to demonstrate the adequacy and feasibility of the scheme and to provide a basis for the preliminary costs estimate.

The retrofitting measures that were evaluated include both turning the structures, to reduce violent actions caused by the ground motions of an earthquake, and strengthening the structures to minimize damage by these actions. The tuning measures can consist of installation of motion isolators and/or dampers, as well as changes in the articulation of the structures with new members, bearings, or lock-up devices. The strengthening measures, applied to members, bearings, connections, and footings, can consist of replacement, strengthening, bracing, and/or construction of redundant parallel systems.

The methodology for this evaluation consists of the following three steps: Evaluation of the seismic risk and generation of site-specific ground motions, definition of performance levels and design criteria, and seismic analysis.

5. SEISMIC RISK AND GROUND MOTIONS.

Site specific ground motion studies were performed to determine the seismic input to be used for the structural analyses of the bridge.

The determination of ground motions was based on evaluations of the geology and topography of the area surrounding the bridge site, seismic risk analyses, and computer simulations of ruptures on nearby faults. The results of these studies are presented in Geological, Geotechnical and Ground motion studies for seismic retrofit of the Golden Gate Bridge in July, 1992[4] by Geospectra, Inc., Richmond, CA.

Regional Geology

Data on the geology of the Golden Gate Bridge site, and estimates of seismic wave velocities of the geological materials, were compiled from original boring explorations done in the 1930s, and eight borins up to 240 m deep and shear wave velocity measurements completed in 1992.

The materials underlying the Golden Gate include (1) sandstone; (2) serpentine; (3) chert; (4) greenstone; and (5) superficial soils. The compiled data also suggest that a uniform shear wave velocity of 4,000 ft per second is reasonable for these ground motion studies.

Seismic Risk

The faults most critical to the seismic risk at the Golden Gate Bridge are the San Andreas fault at a distance of 10 km, length of 880 km, with a maximum credible magnitude of 8.25; and the Hayward fault at a distance of 20 km, length of 124 km, with a maximum credible magnitude of 7.3.

Seismic risk was evaluated by applying a probabilistic assessment of ground motion using the maximum credible earthquake values assigned to the two main faults and other faults in the source region. The risk from random sources not associated with these faults was incorporated as a magnitude-6 random event that could occur anywhere within the source region.

The results of the seismic risk analysis indicate that the peak ground acceleration with a 50 percent and 10 percent chance of being exceeded in a 50-year-period at the site corresponds to 0.28 g and 0.46 g, respectively. The peak ground acceleration estimated for a maximum credible event comparable to the 1906 San Francisco earthquake is 0.65 g.

Design Response Spectra

Site-specific response spectra were developed on the basis of the seismic risk analyses. The shape of the site-specific response spectra is influenced by the source as well as the soil conditions at the site. Therefore equal probability spectral shapes were developed, with the site classified as a rock site. The resulting elastic site-specific response spectra for the 50 percent chance and 10 percent chance of being exceeded in a 50-year life at the site for 5 percent damping are presented in Figure 2, along with the spectrum for a maximum credible event.

Ground Motion Synthesis

The paucity of strong-motion records from large earthquakes has spawned a new science and technology, the synthesis of realistic strong-motion records. Even though the rapid densification of strong-motion stations within the last few years has led to the recording of many large-magnitude earthquakes at relatively close-in distances, time histories of actual earthquakes with sufficient duration and signal content are still not available to satisfy the specific needs of many applications such as long-span suspension bridges.

The synthesis of realistic earthquake records for structural analysis requires adequate consideration of spectrum compatibility as well as all characteristics of the strong ground motions that can be expected at the structure site. The seismic signals from a major earthquake incident upon a structure can be divided into three portions:

1. The onset of motions portion, during which the recording instruments are triggered.
2. The peak amplitude portion, during which the

structure is subjected to strong ground shaking.

3. A much longer coda portion of lower-amplitude shaking during which the surface waves and various reflection waves arrive. In the case of magnitude 8 earthquakes, the coda portion may last up to about 80 seconds. Coda wave durations may be further enhanced by their transmission through alluvial valleys and/or softer materials.

Seismic evaluation of flexible or lightly damped structures such as long-span bridges requires careful consideration of the coda portion. The response of such structures at higher (short-period) modes are excited by the peak amplitude portion of the accelerograms, whereas their lower (long-period) mode are excited by the longer-duration, long-period signals of the coda portion. Because the long-period responses of such structures are likely to be controlled by the coda portion of the ground motions, these responses most likely will occur following the peak amplitude motion.

The primary criteria for synthesizing strong-motion records for the Golden Gate Bridge site are sufficient duration, adequate spectrum compatibility, and appropriate long-period signal content in the coda. Although the peak amplitude portion is evident on acceleration records, the coda portion requires review of displacement records because the long period signal of the original acceleration records is enhanced by their double integration to obtain displacement records.

Two San Andreas bridge site control motions were generated, intended to approximate the April 18, 1906 event. One from a single rupture with a total duration of 60 seconds and the other from a multiple rupture with a total duration of 90 seconds.

For the Hayward fault, the control motions at the bridge site were constructed using a near field record modified for distances, as well as bay crustal effects and the presence of soft bay sediments between the Hayward fault and the bridge site, based on studies of the Loma Prieta ground motion records.

Multiple Support Motion Synthesis

Ground motions for multiple support excitation must contain proper estimates of the phase delays that are reflective of both travelling waves and the velocity of the media in which they travel. The ground motion records must also contain the proper degree of incoherency that reflects the rupture scenarios and wave travel media.

Propagation of the ground motion from the control point at the mid-point of the bridge to the bridge's support points were performed in two steps:

1. Calculation of the dynamic link between the control point and each of the six support points. This link considers the effects of wave type, orientation of the fault segment with respect to the control point, locations of the support points, and response of the materials

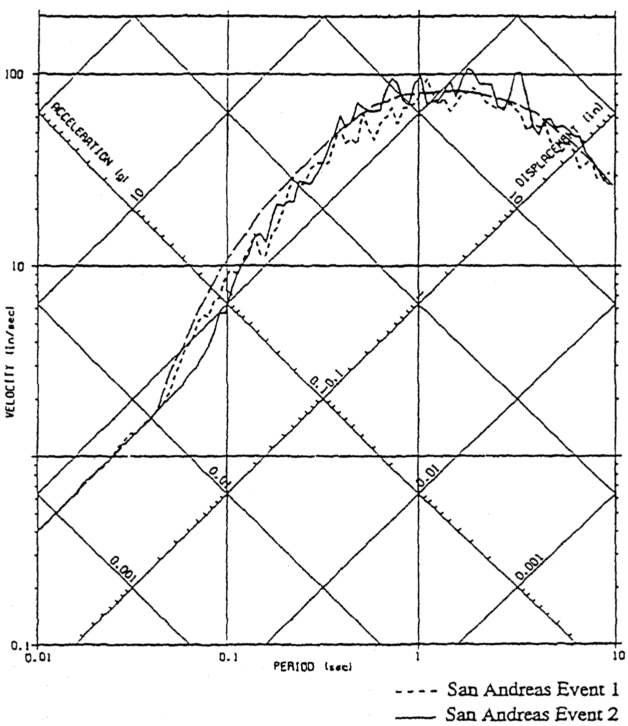

Figure 2. Elastic site-specific response spectra for 50 & 10% chance of being exceeded in a 50 year life; for 5% damping.

below the structure. The link is given in terms of transfer functions which are computed in the frequency domain with the aid of a three dimensional computer program. These transfer functions reflect the relative changes in motion at the bridge support points as a result of the wave travel from different parts of the fault.

2. Propagation of the motions from the control point to the support points by combining the transfer functions with the control motions.

6. SEISMIC PERFORMANCE CRITERIA

The seismic performance criteria for a retrofitted suspension bridge usually presents a compromise between available retrofit measures, constructibility constraints, user expectations, and costs. It may be structurally impossible or too costly to retrofit an existing bridge to survive a major earthquake without any damage. Most seismic codes are based on saving life but not necessarily the structure. But the Golden Gate Bridge is a toll facility and is the only link between San Francisco and points to the north. The retrofit measures for this structure must preserve life and allow the bridge to be used immediately after the largest expected event, first for emergency vehicles and then for the toll-paying general public. To guide the designers in developing the seismic retrofit measures of the Golden Gate Bridge, seismic performance criteria were developed based on policy issues at the owner level and technical issues at the engineering level.

Policy issues include the levels of performance required of the bridge during and after earthquakes, the maintenance of traffic both during retrofitting and after earthquakes, the economics of retrofit versus repair or replacement, the maintenance of the aesthetics and appearance of the bridge, and the maintenance of a proposed future transit corridor on the bridge.

Technical issues include the levels of damage to the bridge that can be accepted and still meet the performance requirements, the appropriate methods of assessing the performance of the bridge to meet the damage constraints, and structural performance that must be provided to meet modern concepts of seismic resistance.

Level of Performance

The level of seismic performance required of the bridge addresses three different magnitudes of earthquake:

1. For frequent but small earthquakes: No loss of traffic capacity is to be expected.
2. For moderate earthquakes: No loss of traffic capacity is to be expected. But some minor damage can occur.
3. For the maximum credible earthquake: Traffic can be interrupted for a short time but the bridge must be restored to operation quickly. This translates into performance criteria that accept limited, repairable damage.

The primary reasons for these criteria are the potential impacts of the loss of the function of the bridge on the economy of the region and the importance of emergency access to the bridge immediately following the earthquake.

Performance Assessment

Current American codes do not set explicit standards for the seismic retrofit of bridges or for the repair and seismic upgrading of damaged structures. While the general provisions of these specifications may be used in instances where applicable, it is necessary to develop additional project-specific standards that address the particular problems inherent in the seismic evaluation and retrofitting of a major structure such as the Golden Gate Bridge.

The seismic performance of the bridge structures, in both their current (prior-to-retrofit) configurations, are assessed, comparing performance demand from ground motion with performance capacity at a limit state with ductility values of 2 to 3.

7. SEISMIC ANALYSIS OF SUSPENSION BRIDGE

The seismic analysis of the Golden Gate Bridge has improved our understanding of the seismic behaviour of suspension bridges similar to the one proposed for the Gibraltar Strait Crossing. The characteristics of suspension bridges, which most significantly influence their seismic response, and the analysis requirements related to those characteristics are summarized below.

Large Displacement Effects

The stiffness of the structure, which is provided mainly by the shape of the cable adjusted to the applied loads, is very sensitive to its geometry. The distortion of this geometry under applied loads causes its stiffness to change as the loads change.

A geometrically nonlinear analysis which considers large displacement effects is required to capture this behaviour.

Multiple Support Excitation

Due to the large distance between supports, the ground motion will be different at each support. These differences are caused by both phase delays due to travelling waves and incoherence created by the travel media and the rupture scenario.

The multiple support excitation imposes relative displacements between the towers and the anchorage blocks that induce both static and dynamic stresses and displacements. The analysis must consider the multiple support ground motion in order to obtain the actual earthquake response.

For the Golden Gate Bridge project, additional analyses also were performed under uniform support excitation, to evaluate the importance of the multiple-support excitation on the peak structural response. The purpose of these analyses was to provide data on the significance of the multiple support problem in the seismic performance of the bridge. The data revealed that, while in most cases the multiple-support excitation causes larger values of maximum response, there are some responses that are larger under uniform support excitations.

Dynamic Characteristics

Due to their dimensions and flexibility, suspension bridges have a long fundamental period of vibrations. The seismic response for long period structures is characterized by large displacements and low seismic forces.

Obtaining the proper response for long period structures requires an adequate description of the earthquake's long period content. Acceleration time histories should be corrected to assure that they do not have a long period content due to a displacement drift which would cause an unrealistically high displacement response.

Although often ignored, secondary vibration modes with a shorter period make an important contribution to the seismic forces. In a response spectrum analysis based on a mode-superposition procedure, it is necessary to consider a very high number of vibrational modes in order to include the modes with a natural period in the range of the maximum spectral acceleration. The high modes have a small mass participation when compared with the total mass but may actually have a very large participation in the response of local elements such as the towers.

For example, in the seismic analysis of the Golden Gate Bridge, it was found that the first longitudinal mode for the towers, with a period of 1.4 seconds, contributed greatly to the towers' seismic forces. However, this mode is the 67 th mode for the bridge as a whole and it would be overlooked in an analysis considering less than 67-mode shapes.

A time history analysis, performed by direct integration of the coupled equations of motion, avoids the problems associated with the mode-superposition method.

Material Nonlinearity

The main cables and suspenders of the Golden Gate Bridge respond to the maximum credible earthquake in the elastic range. Yielding of structural elements is confined to local areas such as towers, pylons and stiffening truss. A similar behaviour is expected for other suspension bridges.

The current practice in earthquake engineering is to design for reduced earthquake loads. This practice is based on the assumption that if the structural members are detailed appropriately, they have significant reserve displacement capacity beyond the initial yielding. This approach has a strong theoretical and experimental basis for structures with fairly uniform distributions of such yielding elements. In the Golden Gate Bridge, however, the structural steel components are not expected to yield significantly. However, the seismic studies of the reinforced concrete pylons suggest that they will yield.

The effects produced by the yielding of the reinforced concrete pylons in the Golden Gate Bridge were studied by comparing the results of two different analyses. In the first, the pylons were modeled as elastic members. In the second, the yielding in bending was modeled with elasto-plastic rotational springs. The results were very similar as far as global behaviour. This fact indicates that an analysis considering elastic material behaviour may give a very good estimate of the actual response, although, it is recommended that material nonlinearities are considered for final design.

Displacement Compatibility

Due to the long natural period suspension bridges have, the seismic displacements are large, on the same order of magnitude as the ground displacements. In addition to this, different parts of the structure are subjected to different ground motions, thus creating large relative displacements at the expansion joints. When the relative displacement at an expansion joint reaches the maximum displacement capacity, the expansion joint closes and transmits impact forces. A joint closure changes the dynamic properties and the response of the bridge. Thus, it is necessary to consider these effects in the analyses by means of nonlinear gap elements.

Support Conditions

It is also important to watch for changes in the support conditions due to seismic forces. In the case of the Golden Gate Bridge, the towers are weakly anchored to the underlying reinforced concrete piers. For service loads, the towers can be considered to be fixed to the piers because the dead load produces compressive stresses which are not exceeded by the bending stresses due to wind loads. However, uplift of the towers can be expected in strong earthquakes. This uplift significantly change the towers response characteristics. The rocking motion of the towers actually reduces the seismic stresses at the towers but increases the deflections.

The nonlinear rocking behaviour should also be considered in the seismic analysis of a suspension bridge designed with a weak moment connection of the towers to the piers.

Because of these characteristics, conventional linear theory of structures provides a poor estimate of the structural response. The seismic evaluation of the Golden Gate Bridge was performed by using the analysis technology described in the next section.

8. STRUCTURAL MODELLING

Several different mathematical computer models of the suspension bridge were studied. Two-dimensional models of the entire bridge were used for preliminary studies of response to vertical and longitudinal components of ground motions. Three-dimensional models of the entire bridge were used for final studies of response to all three components of ground motions. The underlying idea behind the modelling effort was to attain a global model as simple as possible but yet able to reproduce all the significant linear and nonlinear modes of behaviour.

The global model was built with the help of more elaborate local models. A detailed three-dimensional finite element model of the tower base region was used to study the stress distributions and moment-rotation relationships of this critical part of the bridge. Other local models included the stiffening truss, the horizontal struts between the tower's shafts, and the bridge approaches.

The global computer models include representations of all major structural components of the bridge: the main cables from anchorage to anchorage, the suspenders, the towers, the pylons and the tie-down cables inside, and the stiffening trusses. Figure 3 illustrates the three-dimensional global model used for the analyses. While most structural members are modeled explicitly, the suspended stiffening truss system is nevertheless modeled using superelements to reduce the size of the numerical problem. The three-dimensional model consisted of 903 nodes and 1,351 elements, which are assembled into a system of 3,030 simultaneous equations.

9. ANALYSIS TECHNOLOGY

The analysis of the seismic response of the Golden Gate Bridge required the following three steps of increasing complexity: definition of the dead load state, modal analysis and response spectrum analysis assuming linear behaviour, and nonlinear time history analysis, considering multiple-support ground motion.

Definition of the Dead Load State

The dead load state was defined starting with the geometry and dead load corresponding to the time the construction was completed. The dead load and the construction procedure determined the initial stresses. A static nonlinear analysis considering large displacement theory was performed to check equilibrium and to fine-tune the original geometry. The result of this analysis yielded the dead load state at the completion of construction.

The change in the structure's dead load due to the addition of the bottom lateral bracing system and the replacement of the deck were superimposed on the original dead load situation. The deformations and stresses of this dead load situation. The deformations and stresses of this dead load state, computed by geometrically nonlinear analysis, served as the initial conditions for the dynamic analyses.

The Newton-Raphson method, based on tangent stiffness iteration, was used for this static load analysis to account for the large displacement effects.

Modal analysis

Once the dead load state was determined, a modal analysis was performed to compute the vibrational properties. The modal analysis assumes linear behaviour for small deformations from the dead load state. The natural frequencies and mode shapes

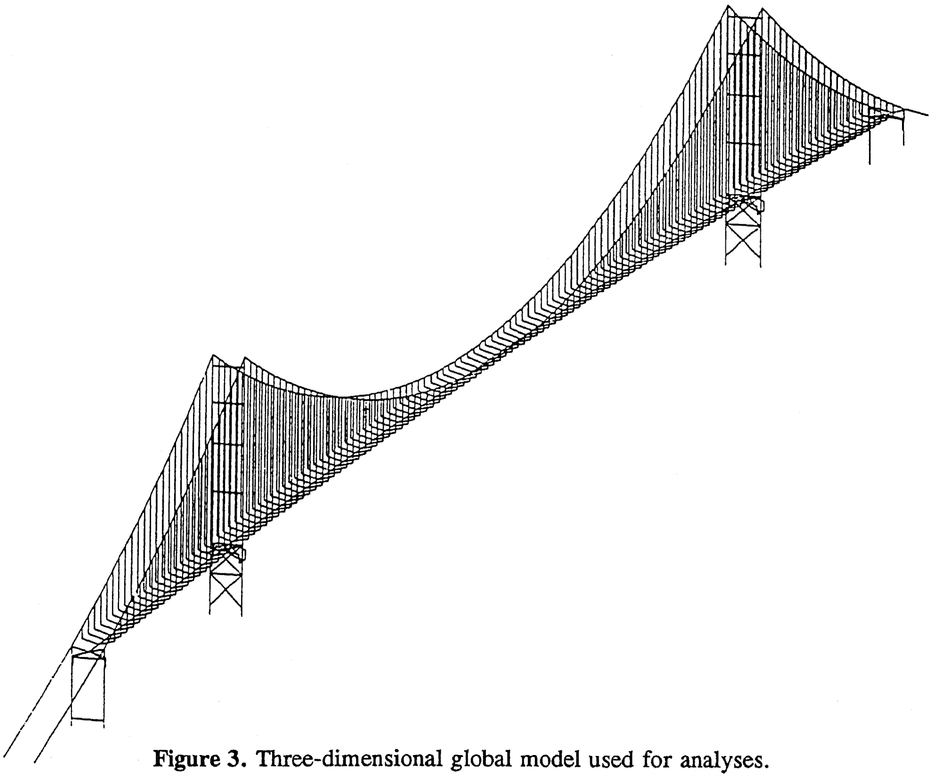

Figure 3. Three-dimensional global model used for analyses.

computed from the analysis were compared with the ones obtained from ambient vibration tests. This comparison provided a way to verify the computer models.

Following the modal analysis, a response spectrum analysis was performed for the maximum credible earthquake. The response spectrum analysis did not include the effects of the nonlinear behaviour or the multiple support excitation. However, it gave an initial insight into the magnitude of the seismic forces, thus redirecting the modelling and analysis efforts towards the problematic areas.

Nonlinear Time History Analysis

The analyses of the global response of the bridge to multiple-support ground motion excitations were performed using a dynamic nonlinear finite element computer program, in which large displacement effects were considered by establishing the static or dynamic equilibrium of the structure in its deformed configuration. The effect of a limited displacement capacity at the expansion joints and the nonlinear uplifting behaviour of the tower's bases was examined by using "gap" elements. The yielding of the reinforced concrete pylons was modeled with elasto-plastic rotational springs.

The nonlinear dynamic analyses were performed by integrating the coupled equations of motion in the time domain by using the acceleration implementation of the average acceleration method. This method is unconditionally stable and has second order accuracy. The ground motion excitation was applied as a time-varying displacement boundary condition at each of the supports. In each time step, the nonlinear system of equations relating the effective dynamic loads and the nodal accelerations was solved by using the Newton-Raphson method, based on tangent stiffness iteration. For some models, a modified Newton-Raphson method that was based on constant stiffness iteration was also used.

Rayleigh damping was assumed, in which the damping matrix is proportional to a linear combination of the mass and stiffness matrices. The proportionality factors were computed to yield a damping ratio of 5% at periods of 0.5 seconds and 20 seconds. The damping ratios for periods between those two values are smaller, with a minimum of 1.5% at a period of 3 seconds. These values are consistent with ambient vibration measurements.

10. SEISMIC DEFICIENCIES TO AVOID IN A NEW DESIGN

The seismic retrofit studies for the Golden Gate Bridge have pointed out seismic deficiencies which should be avoided while designing a new bridge for the Strait of Gibraltar Crossing. The Golden Gate Bridge represented the state of the art in technology in the 1930 s. However, the seismic effects were in their incipient stages. Since then, the advances which have taken place in structural theory, numerical method and computer technology have made it possible to predict the dynamic behaviour of complex structural systems, such as suspension bridges, with a great degree of confidence.

Advances in seismology have also given the engineering community a better understanding of seismic risk. There is more information available regarding ground motions during strong earthquakes and it is thus possible to generate site-specific synthetic ground motions according to local geological conditions. In spite of these advances, there are still many uncertainties regarding the description of future ground motions since they depend on geotechnical conditions that can never be perfectly ascertained, and may be caused by sources which may not previously be known. The long term structural behaviour may also be affected by unforeseen service conditions or by the degradation of structural materials.

In order to increase the overall seismic performance under unforeseen circumstances, a bridge over the Strait of Gibraltar should be designed taking into consideration its seismic behaviour beginning with the conceptual stages.

In addition to providing adequate strength for the predicted seismic forces, the design should be based on the following principles.

1. Ductility: The structural elements, connections and components should be detailed to achieve ductility and avoid brittle failure. The connections would exceed the capacity of the members and yielding should occur before either local or global buckling. The hysteresis behaviour of a ductile structure provides an energy dissipation mechanism which minimizes the probability of member failure or collapse.
2. Redundancy: Alternative load paths should be provided so that the structure can adjust to loads larger than expected by redistributing the load.
3. Displacement Compatibility: A suspension bridge consists of elements with different vibrational properties such as cables, stiffening girder, towers, and anchor blocks. The interface between different elements may have large relative displacements. The design must address this by either leaving enough free space or by keeping the connections between different elements to a minimum. Energy absorption devices such as dampers provide the option of controlling differential displacements but must always include a fail-safe mechanism.
4. The structure should be designed for the ground motions, response spectrum, and seismic risk factor that are expected at the bridge site.

11. CONCLUSION

The seismic retrofit studies for the Golden Gate Bridges have provided a methodology which can be applied to the seismic design of major crossing such as the Strait of Gibraltar. These studies consisted of an evaluation of the seismic risk, a generation of site specific ground motions, a definition of performance levels and design criteria, and finally a seismic analysis.

Some lessons and techniques learned during the seismic evaluation of the Golden Gate Bridge that can be applied to the proposed Gibraltar crossing include the need to consider in the analysis the following aspects: large displacements effects, multiple-support excitation, dynamic characteristics, material nonlinearity and the displacements compatibility and support conditions.

The seismic design of a suspension bridge must provide for adequate ductility, redundancy and must at the same time insure displacement compatibility between different elements.

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