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Seismic Retrofit of the South Pylons for the Golden Gate Bridge

Consolidation parasismique des pylônes sud du pont de Golden Gate

Erdbebenertüchtigung der Südpylone der Golden-Gate-Brücke

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SUMMARY

This paper presents the rationale governing the seismic retrofit design of the Golden Gate Bridge South Pylons, from identifying deficiencies in seismic performance to possible strengthening strategies and final strategy selection. Comprehensive investigations performed on various possible retrofit options are presented. This paper also illustrates the importance of integrating analysis, design and detailing with other design criteria such as reliability, aesthetics, constructibility, serviceability, and economics.

RÉSUMÉ

L'article présente les considérations qui ont conduit au concept de renforcement du pylône sud du pont de Golden Gate, allant de l'identification des faiblesses du comportement sismique jusqu'aux stratégies de renforcement possibles et au choix final de la stratégie. Des études globales ont été réalisées sur différentes possibilités de consolidation. L'article illustre l'importance d'une conception globale de l'analyse du projet et des détails constructifs en fonction d'autres critères de projet tels que fiabilité, esthétique, possibilités de réalisation, aptitude aux service et aspects financiers.

ZUSAMMENFASSUNG

Der Beitrag zeigt die Ueberlegungen auf, die das Verstärkungskonzept für die Südpylone der Golden-Gate-Brücke bestimmen, von der Identifizierung von Mängeln im Erdbebenverhalten bis zur definitiven Konzeptwahl. Dazu wurden umfangreiche Untersuchungen an verschiedenen möglichen Ertüchtigungsoptionen vorgenommen. Die Bedeutung einer integralen Lösung, die ausser den Tragwerksproblemen auch die Zuverlässigkeit, Aesthetik, Bauverfahren, Gebrauchstüchtigkeit und Wirtschaftlichkeit einbezieht, wird deutlich.

1. INTRODUCTION

The two South Pylons, S1 and S2, of the Golden Gate Bridge are two massive under-reinforced concrete bent type structures (see Figure 1). Pylons S1, the northern most of the two structures, is located between the Fort Point Arch and the main Suspension Span. Pylon S2 is located between the South Viaduct and the Fort Point Arch. Pylon S1 is approximately 250 feet tall and is made up of walls of different thicknesses varying from 24 to 36 inches which form both of the approximately 32 feet by 43 feet double cell hollow legs of the Pylon. The legs are joined at the top by a transverse cross beam that consists of two walls, each 48 inches thick and about 30 feet deep. The top of the Pylon supports a 32-foot roadway. In addition to supporting 32 feet of roadway, Pylon S1 provides a tie-down for each of the main suspension cables. It also provides wind lock coonection for the side suspension span. Pylon S2 is somewhat similar in dimension to S1, however, it has less demand placed on it from adjacent structures, therefore its wall thicknesses vary from 18 to 30 inches and the legs are single cell hollow structures. The existing Pylons S1 and S2 weigh approximately 40,000 kips and 30,000 kips, respectively. Both Pylons are supported on spread footings founded on rock and provide support for the Fort Point Arch structure near their base. The existing reinforcement in the walls of the Pylons consists of two curtains of 0.75 inch diameter plain bars at 24 inches spacing, totalling less than 1 % steel, which is significantly less than the minimum required by modern design codes. The corrosive environment due to ocean wave spraying at the bridge has resulted in serious deterioration and spalling of the west walls of both Pylons.

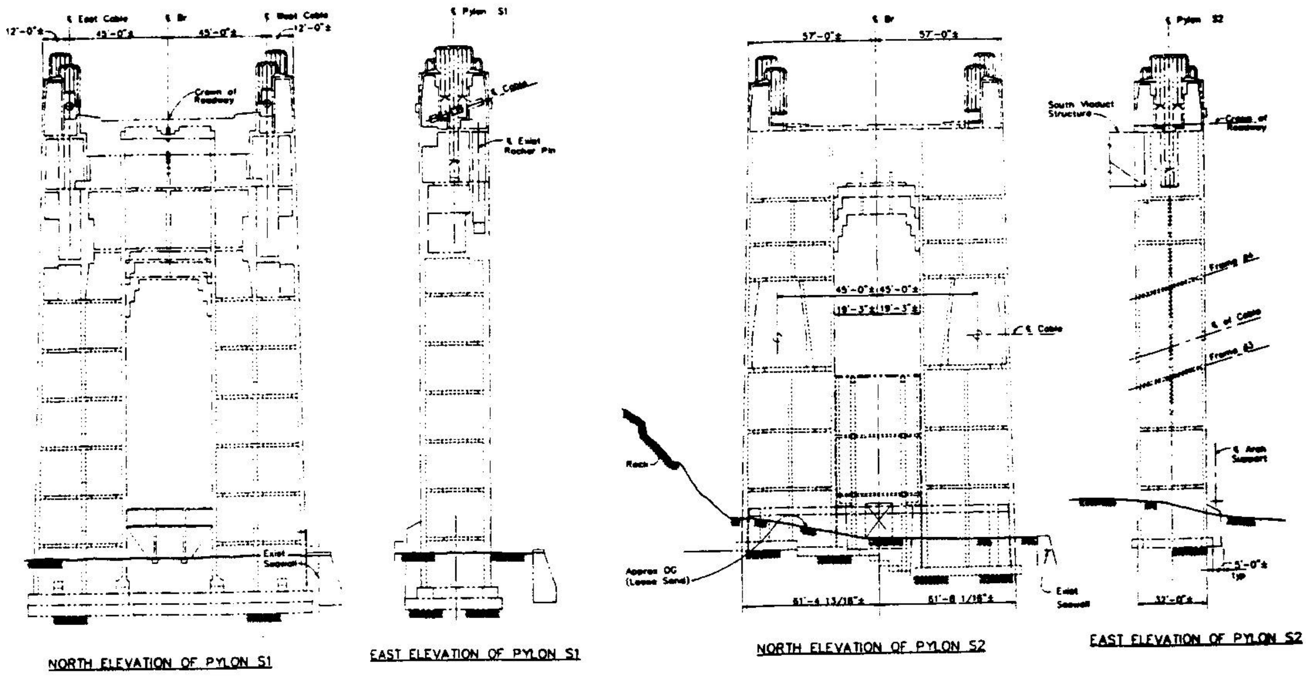

Figure 1: Elevations of Pylons S1 and S2

2. DESIGN CRITERIA AND GROUND MOTIONS:

The goal of the proposed seismic retrofit of the Golden Gate Bridge is to strengthen the bridge so that it will maintain its function after sustaining a maximum credible earthquake (MCE). The importance of the structure and its proximity to two major active faults (the San Andreas and Hayward faults) required 16386Dthe development of a comprehensive project specific design criteria [1].

For seismic evaluation purposes, site specific studies generated three sets of ground motion time histories for the bridge site based on the rupture scenario of the San Andreas fault [2]. These time histories depict acceleration, velocity and displacement in three orthogonal directions at all support points of the bridge, and they also incorporated the effects of seismic source, wave attenuation and passage, and local wave scattering resulting from the peculiar site topography and geology. The magnitude of the time histories were for a maximum credible design event based on 1000 to 2500 year return period.

3. DIAGNOSTIC ANALYSES AND RESULTS:

Comprehensive methodical three-dimensional linear and non-linear time-history analyses were conducted on each pylon to identify the structure's vulnerabilities, damage scenarios and failure modes [3]. Since the height to width ratio of the pylons are large and their foundations are founded on spread footings, preliminary analysis results with a fixed base indicated that overturning would be a problem. The structures would be subjected to forces that would cause uplift early on in the earthquake record during a maximum credible event. Thus, to better predict the response of the structures, uplift phenomenon was explicitly considered by using nonlinear support boundary conditions in the models. The assumption used at the supports was that only vertical movement would be permitted. In addition to the demands placed on the Pylons due to their own self weight combined with seismic loads, the interaction between the Pylons and the adjacent structures were also included in the analysis. These interactions were modeled as time histories of force reactions from the adjacent structures applied to the Pylons.

The seismic vulnerabilities identified from the analysis indicated that the existing Pylons would uplift and since the Pylon walls were very lightly reinforced, severe tension cracking occurred, which under repeated cyclic loads caused severe degradation and subsequent failure.

4. PRELIMINARY RETROFIT SCHEME INVESTIGATIONS:

The diagnostic analyses showed that the existing lightly reinforced concrete wall of the Pylons was not able to resist the tension demands due to seismic loads and that a major retrofit was needed to satisfy the design criteria. The maximum compressive stresses before failure were approximately 30% of the ultimate stress indicating that the Pylon had sufficient compressive capacity. The lack of tension capacity is what caused the Pylon to fail. The results also indicated that the response of the Pylon legs is not like that of a typical column in bending, but instead the walls act like a membrane in either tension or compression. In addition, allowing rocking or uplift at the Pylon base significantly reduced the forces on the structure.

Prior to the development of the final retrofit strategy, several possible concepts for retrofitting the Pylons were methodically investigated in detail. The development process of the most promising options comprises two essential considerations:

1. Strengthening the walls while attempting to minimize the added mass.

2. Displacement compatibility with adjacent structures. The interaction between the Pylons and the Arch, as well as the interaction between Pylon S1 and the Suspension Bridge and between Pylon S2 and the South Viaduct limits the acceptable displacements at the top of the Pylons. Besides retrofitting the structure for seismic resistance, there are other important aesthetics considerations as the Golden Gate Bridge is classified as a historical landmark. The Historic Preservation Act of 1966 and the Secretary of Interior's Standard of Rehabilitation dictates that the defining characteristics of any historical landmark

shall be preserved, which include distinctive features and finishes.

The numerous strategies generated during the preliminary analytical investigations include one or a combination of base isolation, foundation rocking, thickening of concrete walls, steel plate encasement, wall posttensioning, construction of new inner ductile frame, and complete structure replacement.

The retrofit scheme as suggested by the previous studies [4] by adding new interior reinforced concrete walls within each Pylon leg and providing complete base fixity by installing posttensioned rock anchors was found to be impractical and inadequate for the following reasons: First, completely fixing the base invariably attracts excessive seismic base shears and overturning moments which requires an impractical large number of rock anchors. Second, strengthening the Pylon walls on the inside face alone does not help the structure seismically as the outside face of the walls would crack and spall due to the high tension stresses. Third, the mass of the structure will increase by such retrofit scheme which in turn would generate higher seismic demands and thereby reduce the effectiveness of the strength to mass ratio.

Most of the preliminary investigations attempted to maintain the architecture of the Pylons by placing the retrofit on the inside. As the process evolved, however, the high tension and compression stresses on the outside face of the existing walls required strengthening outside as well. As a result, modifying the exterior of the Pylons was necessary. However, any exterior modifications would be architecturally reviewed and approved.

5. FINAL RETROFIT STRATEGY SELECTION:

The need for adequate wall strength is obvious for the Pylons which have very low tensile and ductility capacities due to the minimal reinforcement levels and the absence of confinement steel. Due to the extremely high tension demand on the Pylon walls, a scheme which includes the steel plate "sandwiching" the existing walls while allowing uplift of the foundation was finally accepted (see Figure 2). The scheme requires through ties to provide composite action between the existing Pylon walls and the steel plates. The "sandwich" steel plating scheme was adopted because of its higher strength to mass ratio; its superior strength against two dimensional membrane stresses; its inherent ductility; its more predictable structural behavior; and lastly its relative ease and simplicity in construction.

The foundation will be partially tied down with partially unbonded rock anchors. This was chosen for two reasons. First, allowing the foundation to rock freely results in excessive displacements at the top of the Pylons. Second, completely fixing the base requires an impractical number of rock anchors. The level of tiedown required is determined by sliding resistance to the rocking base shear. A large monolithic combined footing linking both the Pylons legs will be provided (see Figure 3). Not only does this combined footing enhance rocking stability by ensuring that the center of gravity of the rocking mass falls within the base, but it also spreads the stresses more uniformly across the foundation-soil interface to prevent abrupt soil failure beneath the Pylon's foundations. Special detailing attention is given to the interface between the walls and the foundations of the Pylons to ensure structural integrity so that the Pylon walls would not break away from the combined footing during the rocking motion.

The architectural criteria for the Pylon retrofits are focused on retaining most of the dimensional characteristics and the concrete exterior. The basic retrofit concept for the Pylon walls consists of a continuous structural steel plate on both exterior and interior faces of the Pylons with a shotcrete veneer on the exterior face of the walls as shown in Figure 4. Extensive effort was taken to address the constructibility and corrosion protection and structural durability of the steel plates against the highly corrosive environment at the bridge site [5], in addition to preserving the original concrete texture.

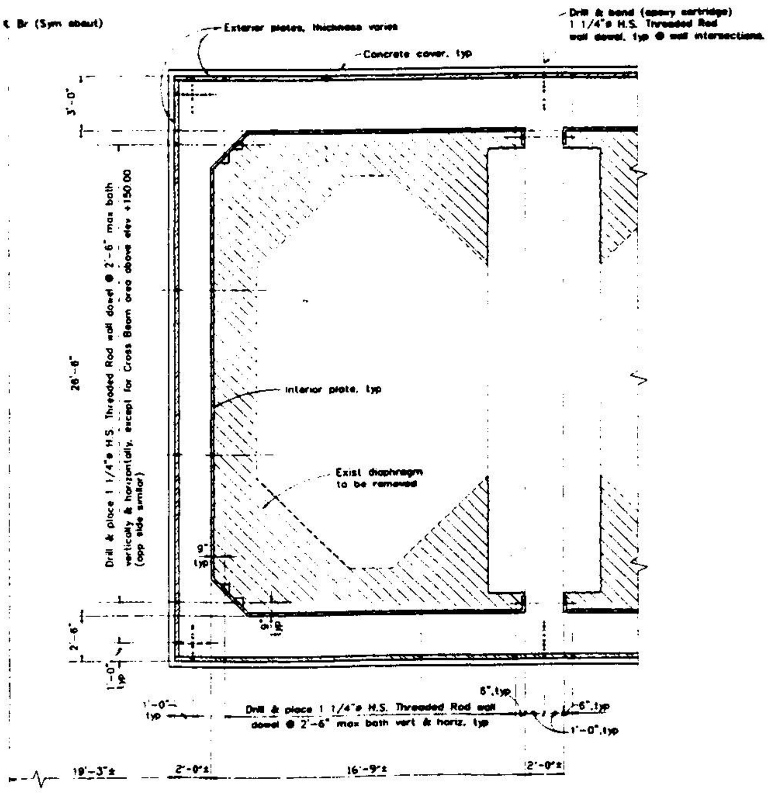

Figure 2: Part Typical Wall Section Showing Steel Plating Arrangement

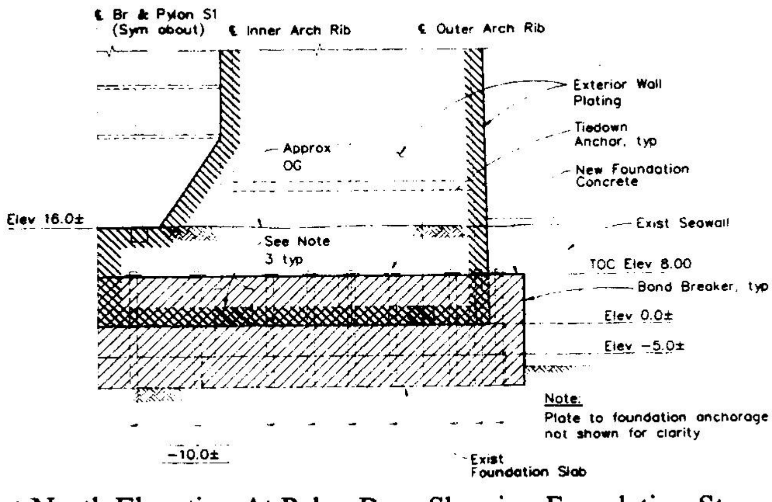

Figure 3: Part North Elevation At Pylon Base Showing Foundation Strengthening

The envisioned construction begins with the removal of the existing cover concrete on the exterior face of the Pylons, including any unsound concrete. The exposed concrete and reinforcement are sandblasted to remove any traces of impurities. The exterior and interior steel plates, in manageable sizes, are then placed and tied together by through ties in stages. Each smaller individual steel plate panels will be field welded together and grout is then pressure injected to seal any void between the steel plates and the existing concrete. A four-inch new concrete cover in two coats is placed on the exterior face. A three inch inner coat which comprises steel fiber reinforced silica fume shotcrete will be placed first with one-inch second coat of shotcrete on top to simulate the original concrete texture. To ensure proper bonding and cracking control, the concrete cover will be reinforced with shear studs and reinforcing mesh.

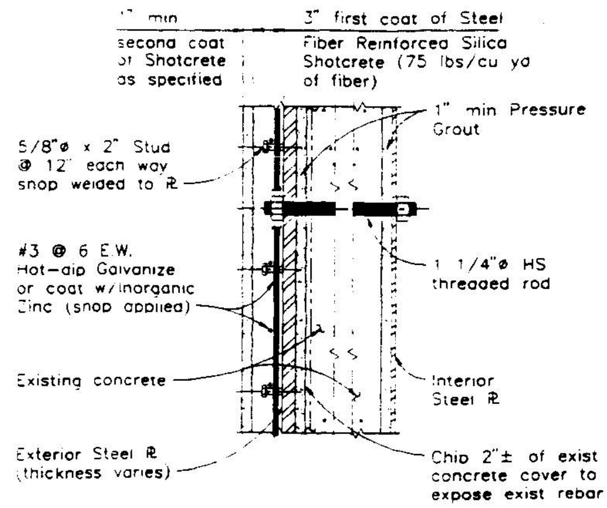

Figure 4: Retrofit Details of Pylon Wall

6. CONCLUSIONS:

The goal of the proposed seismic retrofit of the Golden Gate Bridge is to strengthen the Bridge so that it will maintain its function after sustaining a next major earthquake. The highly under-reinforced nature of the concrete combined with the mass and geometry of the existing Pylons make them very vulnerable to the next earthquake. Extensive linear and nonlinear computer models and analyses were created to determine various retrofit options for the Pylons. Due to the extremely high tension demand on the Pylon walls and the relatively poor condition of the existing concrete, a scheme which includes the steel plate encasement while allowing a certain amount of uplift for foundation rocking was adopted. To meet the corrosion protection and architectural aesthetic project requirements, the exterior steel plating is covered with high density concrete to maintain the original structure appearance. The Sverdrup team is confident that the final retrofit scheme adopted will improve the Pylons' overall behavior, prevent collapse, and maintain serviceability.

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