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Strengthening Landmarks for Improved Seismic Performance

Renforcement des édifices historiques et amélioration de leur résistance sismique

Erdbebenertüchtigung von Baudenkmälern

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SUMMARY

Historic landmarks in California are relatively modern compared with the landmarks of Europe and Asia, but recent experiences in strengthening such structures for improved seismic performance is applicable to their more ancient counterparts. Evaluation procedures, criteria and strengthening techniques are discussed with several recent case studies cited as examples. Creative strengthening techniques not only improve public safety during future earthquakes but protect historic fabric and preserves our landmark structures for future generations to enjoy.

RÉSUMÉ

Les édifices historiques en Californie sont relativement modernes en comparaison avec ceux d'Europe et d'Asie, mais les expériences récentes pour renforcer ces bâtiments et pour améliorer leur résistance sismique sont aussi applicables à des constructions plus anciennes. Une évaluation des procédés, des critères et des moyens techniques de renforcement est discutée dans plusieurs études citées comme exemples. De nouvelles techniques de renforcement améliorent non seulement la sécurité du public lors de tremblements de terre, mais protègent et conservent aussi les édifices historiques pour la joie des générations à venir.

ZUSAMMENFASSUNG

Historische Wahrzeichen Kaliforniens sind verhältnismässig neu, verglichen mit jenen in Europa und Asien. Trotzdem sind die jüngsten Erfahrungen in der Erhöhung der seismischen Tragfähigkeit solcher Bauwerke in Kalifornien auf ihre älteren Ebenbilder anwendbar. Eine Beurteilung der Verfahren, Kriterien und Verstärkungstechniken bilden Gegenstand der mit kürzlichen Fallstudien illustrierten Abhandlung. Kreative Methoden zur Tragwerksverstärkung verbessern nicht nur die öffentliche Sicherheit im Falle eines Erdbebens, sie dienen auch der Erhaltung historisch wertvoller Bausubstanz zur Freude künftiger Generationen.



INTRODUCTION

Many historic and landmark structures located in regions of seismic activity are vulnerable to extensive damage and possible collapse in severe earthquakes. In order to increase the probability that these structures will survive future earthquakes with minimal or repairable damage, it is frequently desirable to strengthen the lateral force resisting system of these structures for improved performance.

Strengthening historic landmarks presents challenging tasks to engineers as strengthening must be executed to meet life-safety and performance goals while minimizing the impact on the historic fabric of the structure. This creates conflicts which require sensitivity to both historical preservation principles as well as realistic seismic performance. This balance between preservation and seismic safety can be achieved, but it requires careful evaluation of alternatives and acceptance of interventions which greatly improve seismic performance with minimal impact on appearance and historic fabric.

The procedures and examples described in this paper are based on experience in the State of California on the west coast of the United States. The landmark structures of California are generally only about one century old as appreciable western civilization came to the west coast of North America only 140 years ago after the discovery of gold in California. Despite the modern character of these California landmarks when compared to the landmarks of Europe and Asia, most of them contain unreinforced stone and brick masonry similar to the more ancient landmarks.

EVALUATION OF SEISMIC RESISTANCE

The first step in the process is to evaluate the seismic resistance of the existing building. Sometimes this is prompted by some damage from a small or moderate earthquake, as has been the recent case in the San Francisco Bay Area following the Loma Prieta earthquake of 1989. This damage from the smaller earthquake usually occurs at weak links in the lateral force resisting system or indicates deficiencies in its seismic resistance. Lacking an earthquake of sufficient intensity to highlight all the structure's vulnerabilities, it is necessary to evaluate the structure carefully using considerable engineering judgment.

The evaluation process first demands a thorough understanding of the structural and nonstructural elements and how they are interconnected. If drawings are not available, this requires drilling or cutting small holes or performing nondestructive testing to determine weights and composition of elements. Connections between elements are particularly important and must be verified. The strength of key structural elements should be determined by testing. In addition to concrete and steel testing by removing samples, the most common test is an in-place push test to evaluate the strength of masonry mortar in shear. The common test now being used in California for brick masonry involves removing a brick and the mortar from the end of the adjacent brick, inserting a hydraulic jack in the space of the removed brick and determining the in-place shear strength of the mortar.

The evaluation process is always based on a conventional lateral force and gravity analysis of the structure. However, the analysis must also be based on considerable engineering judgment and a sound understanding how similar landmark structures have performed in past earthquakes. In addition to evaluating basic wall and horizontal diaphragm strength, the interconnection between these elements must be carefully considered. A complete stress path must be evaluated throughout the structure. All elements must be tied together, as historic floor or roof arches and walls tend to spread and lose their structural integrity in

strong shaking. Discontinuities in the lateral force resisting system need to be carefully evaluated as historic structures seldom have the ability to adequately transfer lateral forces to other bracing elements. Common sense and sound engineering judgment based on experience is needed more than sophisticated analytical procedures.

Criteria for the evaluation is also necessary and important. Building codes in force have been developed for new construction and seismic resistance requires proper material detailing for ductility. Unreinforced masonry is not permitted as it exists in the landmark structure. Thus, a code or criteria recognizing archaic materials is essential. The State of California has developed a State Historic Building Code which gives latitude to engineers to exercise judgment in assigning seismic resistance to archaic materials.

The evaluation will lead to a decision of seismic adequacy of the landmark or if seismic strengthening is required.

STRENGTHENING THE LANDMARK STRUCTURE

Strengthening a landmark structure can take many forms. It can consist of only adding some ties or other elements to correct a specific deficiency. It can consist of strengthening connections between walls and floors or it can be more extensive and add new bracing elements. Whatever solution is selected, it must be selected considering the historic fabric of the landmark and minimizing its impact on the historic features of the structure. Some impact is usually necessary and tradeoffs between structural integrity and historic preservation must be carefully evaluated.

The most common strengthening methods being utilized to strengthen landmarks include:

1. Adding reinforced concrete shear walls or buttresses. These may be new walls or shotcrete walls added against the historic masonry with finishes restored. Sometimes a wythe or two of masonry is removed and replaced with reinforced shotcrete so interior wood trims and ceilings will fit to original dimensions.
2. Adding structural steel diagonal bracing. Unfortunately, this system seldom achieves sufficient stiffness to protect the masonry from damage. Once the masonry cracks, the steel bracing can act and maintain structural integrity.
3. Seismic or base isolation consists of rebuilding the foundation to incorporate isolators that reduce the propagation of ground motion into the building. This method requires adding the isolators near the base of the structure and appropriate strengthening of the structure compatible with the isolation system. Criteria has recently been developed and design is currently underway to incorporate such systems in five or so San Francisco landmarks.
4. Center-coring consists of coring vertically down through masonry and grouting a reinforcing bar in each cored hole to reinforce masonry. The cores are usually wet-drilled although a technology has been developed to dry core so finishes do not have to be removed if susceptible to water damage. This system has been used, although improvements in directional control of the coring would be desirable and further testing is needed to give engineers confidence in design procedures.



The following are several examples of recent California projects:

Ferry Building - San Francisco

San Francisco's Ferry Building was built in the 1890s at the edge of San Francisco Bay on land fill. The three-story structure is about 200 m by 45 m in plan with reinforced concrete floors supported by structural steel beams and columns. The first floor columns are primarily cast iron. The roof is wood sheathing on light steel trusses and the facade is sandstone backed with brick. A tower rises from the center which is about 10 m square and 55 m high. The tower is framed with structural steel including eyebar diagonal X-bracing. The facade is sheet metal over wood above about 35 m. The foundations are timber piles through about 30 m of soft clays to sand bearing below. Figures 1 and 2 illustrate the building.

The building was heavily damaged in the 1906 San Francisco earthquake when eyebars in the tower both failed and permanently elongated about 50 mm. The sandstone on the tower was heavily damaged and replaced with reinforced concrete after the earthquake. Sandstone and brick infill in the low-rise was also damaged and repaired.

With the termination of ferry services in the 1940s after the Golden Gate and Bay bridges were constructed, the Ferry Building was converted to office and commercial space. The high Second Floor waiting room was compromised by adding a full Third Floor. The two sides of the building were altered at different times, the north half in the 1950s and the south half in the 1960s. A more substantial interior concrete wall system was added in the northern half while more of the historic fabric and finishes were maintained in the southern half.

The 1989 Loma Prieta earthquake caused more damage. Several columns in the tower buckled where the X-bracing had eccentric working points. The steel flagpole atop the tower bent as it did in 1906. The front facade of the low-rise aligning with the tower was permanently displaced about 20 mm. There was various damage and cracking of the masonry walls and parapet in the south half and the end wall cracked, failed its few connecting bolts to the roof and separated about 5 mm from the roof. There was no damage in the north half which was stiffer and stronger for lateral forces.

The United States federal government pays for repairs to local government buildings such as the Ferry Building through the Federal Emergency Management Agency (FEMA). Thus, the basic damage to the tower, flagpole and cracked masonry is being repaired. We were able to convince FEMA that the most suitable repair of parapet damage was to brace the parapet with reinforced concrete and steel braces. The sandstone facade in front of the tower that was permanently displaced will be left displaced but the stones will be anchored to new reinforced concrete backing. This includes the decorative facade columns which are a series of round or square stones atop each other with no steel reinforcement. The cracked and slightly leaning south wall will be reconstructed by removing two wythes of brick from the exterior (250 mm thick) and replacing it with reinforced concrete anchored to all floors and the roof. This new concrete both repairs the south wall damage, significantly strengthens the end of the building, preserves the historic interior brick and stone arched window at the Third Floor and allows us to restore previous modifications in the south wall by replicating the original arched windows and tracery. FEMA also agreed to fund these improvements as repairs.

Based on a detailed analysis at the beginning of the project, we also recommended adding some additional interior reinforced concrete shear walls beneath the tower and in the south half of the building. This work is also being funded by FEMA as a reasonable measure to reduce damage in future earthquakes. Care is being taken on locating these walls to minimize their impact on the historic fabric remaining on the interior of the building.

Memorial Church - Stanford University

Stanford University is located about 50 km south of San Francisco. The Memorial Church was built by Jane Stanford between 1899 and 1902 as a memorial to her husband, Leland Stanford, Jr., who founded the University. It was built in the classic cruciform shape with the nave, transepts and chancel meeting in the crossing, an area bounded by four tall stone and brick arches supporting a 15 m diameter dome and four mosaics on plaster of the archangels. The Church was built of unreinforced stone masonry with wood roof and a steel supported tower above the dome of the crossing. The new Church was severely damaged in the 1906 San Francisco earthquake and was completely rebuilt with reinforced concrete walls with stone veneer except for the crossing. The steel tower was removed above the interior wood and plaster dome. Figure 3 is an overall photograph of the Church.

In the 1989 Loma Prieta earthquake, the "new" concrete walls performed well but the original arches of the crossing were damaged. The arches are about 22 m high and each consists of two 1.6 m deep by 550 mm wide stone arches with carved faces. The pairs of arches support a brick wall and are separated by a void about 0.5 m wide where the structural steel for the original tower is located. In the 1989 earthquake, several of the arches moved perpendicular to their plane and caused stones near the center of the arch to crack and drop about 25 mm. At the junction of the arches, the plaster mosaics were damaged with a portion falling to the floor below.

The damage was analyzed, the conditions determined and an analysis was completed. It was decided to strengthen the arches by filling the void in their center with some heavily reinforced concrete, to provide a diaphragm at the top of the walls above the arches consisting of a substantial reinforced concrete cap beam and steel diagonal braces. The added steel included a stiff downward cantilever to stiffen the arches against perpendicular movement. The reinforced core between the arches was also tied horizontally to the reinforced concrete walls of the four projections from the crossing to improve structural ties and the transfer of lateral forces. The wood roof diaphragms over the entire Church were strengthened with new plywood and stronger ties and connections at the concrete walls. All of this work was completed in concealed locations with no visible evidence of the repairs and strengthening. Figure 4 illustrates the strengthening scheme.

The decorative mosaics at the corners of the crossing were found to have partially debonded from their supporting plaster in addition to the portion that fell. An elaborate support system was developed to maintain the mosaics in their location while the plaster backing and a new fiberglass backing to steel supports was installed. Tests were conducted to insure adequate bonding of the fiberglass to the mosaics and the steel supports including epoxy products to insure bonding to some steel supports.



Museum of Art - San Jose

The Museum of Art in San Jose, about 70 km south of San Francisco, was built as the United States Post Office about 1890. It is a two-story plus basement structure with an 18 m high clock tower. The exterior walls are rough cut sandstone with brick backing and are bearing walls. Floor construction consists of brick arches supported by steel beams and girders spanning to cast iron columns. Figure 5 illustrates the building.

The building was extensively damaged in the 1906 San Francisco earthquake when the tower collapsed. The building was rebuilt with minor revisions to the top of the tower. In the 1989 Loma Prieta earthquake, there was minor damage consisting of cracking in the tower near the bottom of the 1906 collapse. There was no damage in the lower floors, but in a partial Third Floor attic slab, there was significant cracking at locations where the steel framing and brick arches changed directions. At those locations, there were no continuous tension ties in the floor diaphragm to prevent spreading and resist tension forces. In the lower floors, both the steel beams and the girder-to-column connections were bolted for continuity, providing tension capacity for the floors.

The tower and Third Floor attic have been repaired by strengthening, again funded by FEMA. The tower was strengthened by removing two wythes of brick on the interior and installing reinforced concrete applied as shotcrete. The brick was removed to keep room sizes and window recesses unchanged so original wood finishes could be reinstalled without modification. The Third Floor attic was strengthened by welding steel straps to the exposed top flanges of the steel beams in the unfinished attic to provide tensile ties in both directions of the attic slab.

A second project has completed the design phase to strengthen the remainder of the building. This is to comply with a retroactive ordinance of the City of San Jose requiring all unreinforced masonry bearing wall buildings to be strengthened or demolished in the interest of public safety. The strengthening scheme for the remainder of the building also includes reinforcing the exterior walls with reinforced concrete installed as shotcrete to strengthen those walls. Again, two wythes of brick are being removed in most places so original finishes can be restored. In addition, a new interior reinforced concrete shear wall is being added in the First Floor and Basement beneath a brick wall which forms the exterior of the reduced size Second Floor. These walls are being added to minimize horizontal stress transfers in the relatively weak Second Floor diaphragm so it does not have to be strengthened. New foundations are being constructed beneath the new walls and between the original spread footings. The strengthening work is shown on Figure 6.

CONCLUSIONS

Seismic strengthening of landmark structures is often desirable in regions of high or moderate seismicity to provide public safety as well as to preserve our historic heritage of buildings for future generations. Historic and landmark structures are among the most vulnerable in strong ground shaking and often subject to possible collapse.

Strengthening is performed after a thorough evaluation of the seismic resistance and potential performance of the structure. The evaluation is always based on an analysis of the structure but very strongly influenced by engineering judgment based on knowledge of how similar landmark structures have performed in past earthquakes.

Strengthening usually involves adding sufficient strength and stiffness to resist a significant percentage of the lateral forces, to prevent partial or complete collapse and to protect brittle historic fabric so the building will be easily repairable following a major earthquake. Since most landmark structures are at least partially built of unreinforced brick or stone masonry, strengthening most usually consists of adding reinforced concrete shear walls, often installed pneumatically as shotcrete. Other systems, such as adding steel diagonal bracing, providing a base isolation system combined with judicious strengthening or reinforcing the masonry by the center coring technique is possible. Important aspects of most strengthening schemes in insuring that the structure is positively tied together with adequate continuous tension capacity in all horizontal diaphragms and properly bracing all parapets and anchoring exterior stones and ornamentation to the structural system.

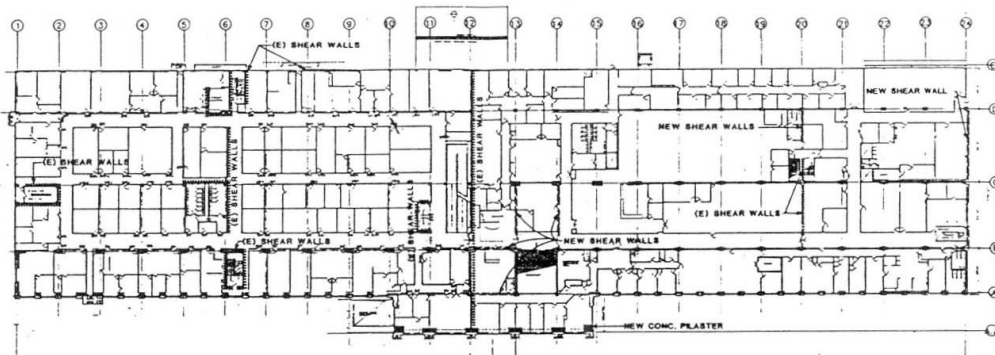


Figure 1. Second Floor of Ferry Building showing existing and recommended locations of shear walls. The tower is between columns 12-13-A-B.



Figure 2. Photograph of Ferry Building tower after Loma Prieta earthquake with bent flagpole.

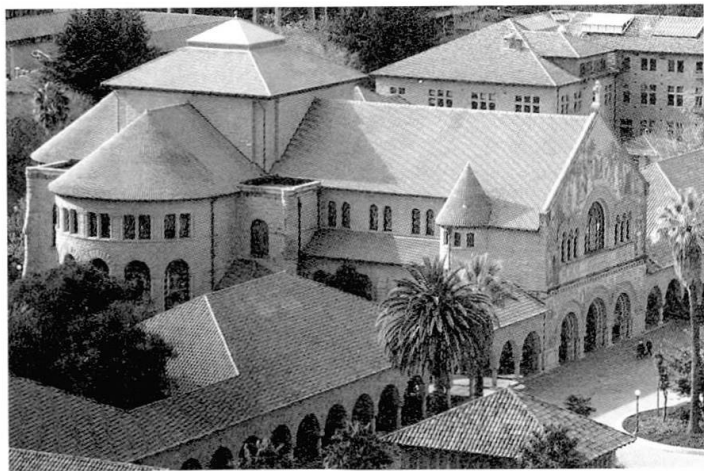


Figure 3. Stanford Memorial Church, Stanford University.

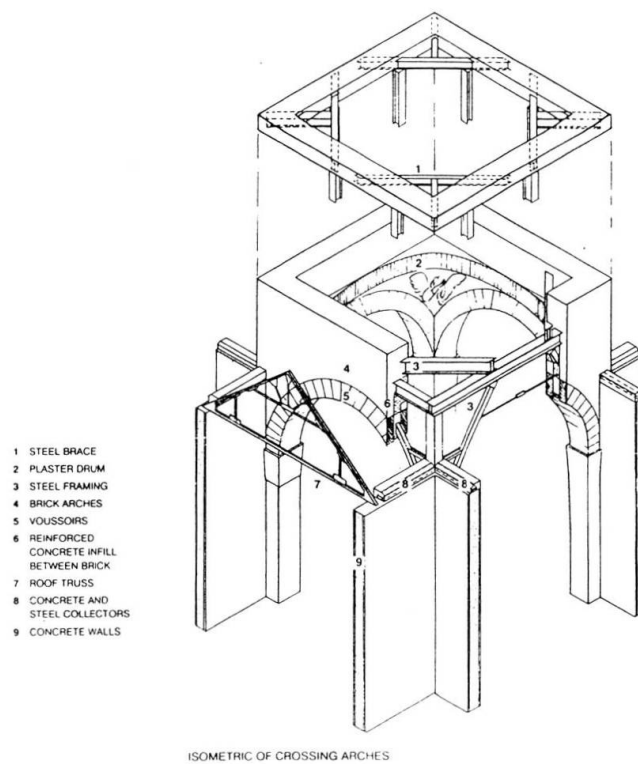


Figure 4. Isometric of strengthening of the Crossing Arches of Stanford Memorial Church.



Figure 5. San Jose Museum of Art, formerly the United States Post Office.

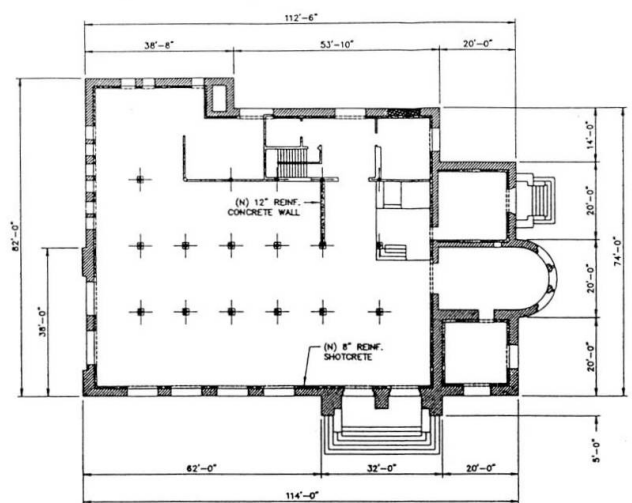


Figure 6. Proposed strengthening of San Jose Museum of Art - First Floor Plan.