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Seismic stabilization of heritage structures in California

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Abstract

Historic heritage buildings and monuments are unique structures in California. These structures include bridges and lighthouses, turn of the century factories, churches and hotels, and many of the residential and commercial buildings that form the core of the older cities. Most of California is very seismically active, but few of these heritage buildings have what is currently considered to be an acceptable safety margin against seismic failure. Many structures were demolished but, fortunately, careful consideration is now given to preservation and seismic stabilization of a historic heritage structure before it is subject to demolition or ill-conceived rehabilitation.

1 Introduction

Historic structures must be preserved for future generations because of their valuable cultural heritage and because they represent an important part of the present housing stock and economic infrastructure. It should be our responsibility to safeguard our cultural resources, and to maintain and preserve our historic heritage buildings in an unspoiled a state as possible. We must also insure that these structures can withstand, not only the deteriorating effect of age and environment, but also the devastating attacks of the elements, such as wind and earthquakes.

Most historic heritage structures in California are not in conformance with current building regulations in regard to life safety and earthquake resistance, and they are often considered potentially dangerous. Seismic stabilization is usually triggered by remodeling, change in use or occupancy, or adoption of a new public regulation, such as an unreinforced masonry ordinance, that sets higher life safety standards.

Seismic stabilization of heritage structures frequently involves trade-offs and compromises. It is desirable to achieve a higher level of public safety and to minimize seismic damage to the structure, but it is also important to preserve the historic fabric. To minimize the impact on the historic fabric there is a tendency to use a lower seismic design criteria for heritage structures, but sometimes, it is argued, a much higher level of stabilization might minimize damage in future earthquakes and in that way better preserve structures for the next generations.

2 Development of Seismic Standards in California

The devastating effect of earthquakes in California have been known for a long time but the 1927 Uniform Building Code was the first to include special seismic design requirements and it was not until the 1940's that seismic resistant requirements were extended to all types of building construction. Since then seismic design requirements for buildings in California have each year become more strict and detailed in response to earthquake experiences both in the United States and the rest of the world. Seismic design requirements are, today, mandatory for all new construction, but they are not always mandatory for existing buildings.

In California any structure constructed prior to the adoption of codes requiring earthquake resistant design, and this includes most heritage buildings, is generally considered potentially hazardous, but conformance to seismic regulations that provide for acceptable life safety standards for the public and for the occupants of the building is not always required. California is currently developing a program for identifying and mitigating seismic hazards in many existing structures. As the first phase, the program includes the more than 60,000 structures of unreinforced masonry construction. The program will require that the owners of these structures, within the next few years obtain a seismic evaluation and, if necessary, strengthen the structure to mitigate earthquake hazards. Many of the large and monumental historic structures in California are constructed of unreinforced masonry construction and this program will affect them. In addition, substantial repair, alteration and reconstruction or new occupancy or use of any heritage structure will trigger a requirement for conformance to current seismic standards. These standards are contained in the seismic building codes, which are typically uniformly applied in California.

3 Seismic Building Codes and Standards

The Uniform Building Code (UBC) is mandatory for all new construction and for additions to or major remodels of existing buildings. The regulations for listed historic buildings are found in State of California Historical Building Code (SHBC), while the Uniform Code for Building Conservation (UCBC) is intended to supplement the SHBC but can also be used for older non-listed buildings.

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3.1 Uniform Building Code (UBC)

The regulations in the UBC are mandatory for the design and construction of all new structures and for additions to existing structures. It is the intention that structures designed in conformance with these regulations should [1]:

- Resist a minor level of earthquake ground motion without damage.
- Resist a moderate level of earthquake ground motion without structural damage, but with some non-structural damage.
- Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as non-structural damage.

The level of damage depends upon a number of factors, including the building configuration, type of lateral force resisting system, materials selected for the structure, and care taken in construction.

3.2 State of California Historical Building Code (SHBC)

Regulations for rehabilitation and retrofit of historical structures in California were first enacted in 1976. These regulations apply to all structures listed or eligible for listing on national, state and local registers, such as the National Register of Historic Places, State Historical Landmarks and City and County Registers. The intent of the code is to provide means for the preservation of California's architectural heritage by recognizing the unique construction problems inherent in upgrading historical buildings. Concurrently, the code intends to provide reasonable safety from fire and seismic hazards for the occupants of such buildings. It is specifically stated, that it is not the intent to protect the property if, by doing so, the historical integrity of the structure is adversely affected [2].

The SHBC applies to all historic structures that are listed or would qualify for listing. All other important structures, which do not qualify for listing, are excluded and any stabilization or retrofit of these structures must comply with the governing local code (often the UBC). Also, if the structure has a high number of occupancy or a particular vulnerable population, such as in schools, hospitals, police and fire stations, the stabilization must always, even when the structure is listed, comply with the higher standards of the UBC.

The regulations in the SHBC are performance-oriented and seismic resistance by archaic materials is permitted. The SHBC contains alternative structural regulations that are applied by an architect or engineer experienced in earthquake resistant design. The SHBC earthquake design force for a structure, generally 75% of UBC, is compared with the earthquake resistant capacity. The evaluation, based upon the ultimate capacity of the actual structure, gives due

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consideration to ductility and reserve lateral resisting strength of materials and systems. The engineer may exercise broad judgment regarding the strength and performance of archaic materials not generally recognized by prevailing code requirements. Past performance of the structure or similar structures may also be used in the evaluation.

3.3 Uniform Code for Building Conservation (UCBC)

Additions to an existing building are required to conform to the UBC, but a newly developed code, the UCBC, can oftentimes be used for alterations and retrofit of existing heritage buildings. This code, recognizing that the retrofit required to bring existing heritage structures into strict compliance with the UBC is sometimes not feasible, is designed to preserve the inventory of existing buildings by identifying a minimum level of safety and performance [3].

4 Seismic Stabilization Criteria

Earthquakes expose a structure to dynamic forces, which must be considered in the seismic stabilization design. The structure must provide a continuous transfer of these forces to the foundation. A well-designed seismic stabilization of a heritage structure should improve the strength, the ductility and the redundancy of the structure. Earthquakes will expose any weakness in the design concept or detailing, therefore, vulnerable links in the lateral load resisting system must be addressed in the seismic stabilization.

The challenge with the seismic stabilization of heritage structures is to find the balance of intervention that reduces the risk for injury or property damage to an acceptable level without unduly destroying the historic fabric. This requires ingenious solutions from the design professional and it often entails making choices between life safety and property damage mitigation at one hand and preservation on the other. It requires allowing large deformations during the earthquake in order to reduce force levels, but it also requires controlling the deformations in order to limit damage to the heritage structure and its contents.

5 Seismic Stabilization Techniques

Many heritage buildings were well designed and constructed for moderate lateral resistance, but current standards strive to provide life safety in major earthquakes. We expect that the historic fabric be preserved and potential damage from earthquakes minimized. No two historic structures are alike and methods for their seismic stabilization are numerous and often unique. There are two general approaches to seismic stabilization. One approach increases the lateral load resisting capacity of the structure, while the second approach reduces the demand of the seismic forces. The capacity of the structure is increased by:

- Strengthening or reinforcing shear walls, floors and columns of the original structure.
- Installing new lateral load resisting elements, such as shear walls, diagonal bracing or moment frames.

The lateral seismic load demand on the structure is reduced by:

- Installing energy dissipating systems, such as base isolation and damping devices.

Several seismic retrofit projects for major structures combine the two approaches. The combination of approaches often minimizes the impact of stabilization on the historic fabric.[4].

6 Seismic Stabilization of Heritage Buildings

The number of heritage buildings in California is in the hundreds of thousands. The use of these buildings, their historic significance, age, seismic vulnerability, and the availability of funding are all important considerations in the stabilization strategy. Different building uses, such as hospitals and schools, require enhanced levels of seismic performance; some materials, such as unreinforced masonry and non-ductile concrete frames, have historically been found to perform poorly; a historic building may require careful rehabilitation, while less significant structures, near the end of their economic life, may not warrant much stabilization work. The problems and the varied methods of stabilization for four basic types of construction are discussed:

6.1 Wood framed buildings

The typical California wood framed heritage building is a residential structure, one to three-story high. It has unreinforced masonry foundation and basement walls, exterior stud walls with cement stucco or nailed wood sheathing, wood floors and roofs, and plaster finished interior partitions. A simple seismic screening of a wood framed structure may be performed by a house-owner, even without engineering experience. Using preprinted forms from the government the expected horizontal seismic force is compared to the horizontal shear strength of the lowest level walls. If the seismic demand force is found to exceed the wall strength capacity, the structure is vulnerable and stabilization is recommended.

Many wood framed heritage structures are vulnerable to seismic damage and often require strengthening of the lower level walls and floor diaphragm. Other weak elements include large openings in first floor walls, such as storefronts or garage doors. Typically, basement walls and first floor diaphragms are strengthened by adding plywood shear panels or bracing, the exterior wood siding is re-nailed to improve shear capacity and control deformations, the walls are secured to the foundations, and the chimneys are braced to the structural framing.

6.1.1 Case study: Pardee Home Museum, Oakland, California

The Pardee Home, listed on the National Register of Historic Places, was built in 1898. The two-story building, with a cupola, is of balloon-framed construction and the exterior walls have diagonal wood sheathing under horizontal wood siding. The freestanding structure rests on a brick foundation. The floors are wood framed with straight sheathing and finished wood flooring. The full height wood stud interior partitions have a plaster finish over wood lath. The house is filled with the artifacts of the four generations of the Pardee Family, and the seismic stabilization had to avoid disturbing the ornamental wall finishes and the artifacts [5].

The decision to open the building as a public museum triggered a requirement for a seismic stabilization. Since this is a listed historical building the alternative structural regulations in SHBC could be applied. The building was in good condition and the weakest link in the seismic resisting load path was below the first floor level. The selected seismic stabilization design, which avoided interventions in the interior of the building, included the following elements:

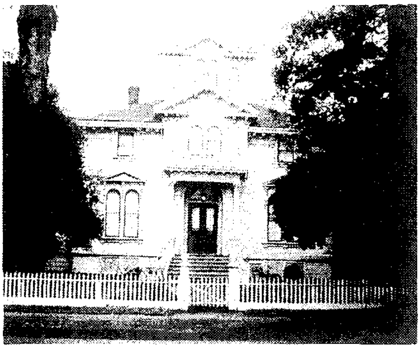

Fig.1: Pardee Home Museum

- The original brick foundation was left in place, mortar joints were repointed and the wood framing was bolted to the foundation with threaded rods grouted into the masonry.
- Selected interior walls in the space below the first floor level were braced with nailed-on plywood panels.
- The first floor diaphragm was stiffened by nailing plywood panels to the underside of the wood floor framing.
- The exterior walls of the entire structure were strengthened by re-nailing the existing wood siding to the balloon-framed studs.

6.2 Unreinforced masonry structures

Heritage masonry structures, typically one to twelve stories high, have unreinforced masonry bearing walls with floors, roof and partitions of wood construction. Effective anchorage of masonry walls to the floors and roof is generally missing and the lack of reinforcement in the masonry, coupled with low strength mortar and inadequate wall ties, often result in severe earthquake damage to these structures as a whole or to individual sections of the masonry.

Unreinforced masonry structures are considered hazardous during an earthquake. Different methods of seismic stabilization have been used, such as installing exposed backup steel frame systems inside the structure, or strengthening the existing walls by removing part of the masonry wall thickness and replacing it with reinforced concrete. In some seismic retrofits the existing masonry has been internally reinforced by coring the walls from the roof to the foundation and placing reinforcing steel in the grout filled voids.

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6.2.1 Case study: St. Paulus Lutheran Church, San Francisco, California

The church, built in 1892, is typical of many inner city churches from this period. With unreinforced brick walls, wood framed floors and roof, and facades with large rose windows and a tower-and-a-half; the church reflects the European origin of their builders and congregation. The poor performance of unreinforced masonry in an earthquake has created concern about these structures and some seismic stabilization is now mandatory. St. Paulus is a listed landmark structure and the retrofit could be performed in accordance with the SHBC. The weak elements of the church were the lack of stability of the tall exterior walls; the connections from the wood framed floors and roof to the masonry walls; and the timber framed towers.

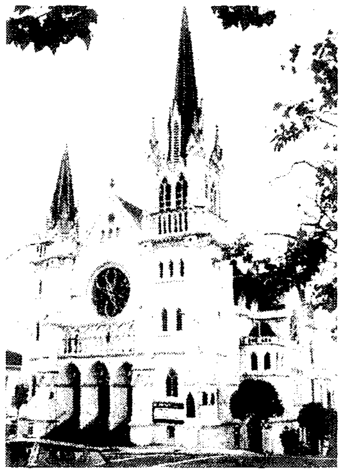

Fig. 2: St. Paulus Church

Although recently lost to fire, the design for the stabilization included:

- The existing timber roof trusses and their horizontal bracing were selectively strengthened with new steel sections. The connections between trusses and their supporting masonry walls were reinforced.
- The timber framing for the church towers was selectively strengthened with steel sections and the connections were reinforced.
- The exterior masonry walls below the first floor were stabilized by removing a layer of bricks from the inside wall face and replacing it with reinforced concrete.
- The exterior masonry walls were stabilized by coring the walls from the top of the wall to below the first floor and placing reinforcing steel in the grout filled holes.

6.2.2 Case study: Geneva Office Building, San Francisco, California

The two-story and basement office building was built in 1901. The structure has exterior walls of unreinforced brick masonry and wood framed floors, roof and interior partitions. The masonry walls suffered damage in the 1906 and again in the 1989 quake. The building is a listed landmark and the stabilization design followed the requirements of the SHBC. The weak elements of the structure are the low shear strength and lack of stability of

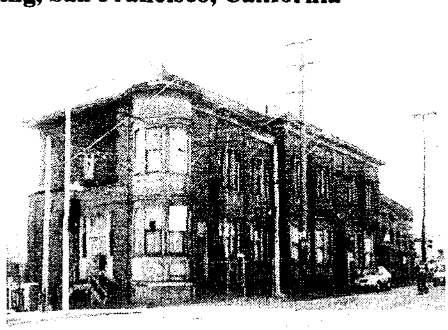

Fig. 3: Geneva Office Building

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the masonry walls and the missing connections from the wood floor and roof framing to the masonry walls. The strategy for the seismic stabilization was to increase the lateral shear strength of selected sections of the masonry, improve the stability of the exterior walls and to improve the anchorage between horizontal framing and the vertical walls. The design for the stabilization included:

- Renail roof and floor sheathing to improve diaphragm action.
- Strengthen the timber roof trusses with steel sections. Reinforce connections between trusses and their supporting masonry walls.
- Anchor floor framing to the masonry walls in order to stabilize walls and to improve diaphragm action.
- Improve the shear capacity of the masonry walls by repointing the bricks. Stabilize selected wall sections by removing the inner layer of bricks and replacing it with reinforced concrete. Stabilize other selected sections by applying epoxied fiber reinforcement to the interior face of the wall.

6.3 Concrete structures

Concrete heritage structures include cast-in-place bearing wall type buildings; concrete frame buildings; concrete bridges; and a great variety of special structures. Some of these concrete structures, where reinforcing was not detailed nor installed to give ductile performance, have performed poorly in earthquakes.

6.3.1 Case study: Donner Summit Arch Bridge, Truckee. California

The Donner Summit Bridge is a 72-meter long fixed arch bridge of reinforced concrete. It was built in 1925 at the top of the mountain pass named after an emigrant party that perished in a snowstorm when crossing the Sierra in 1849. Harsh environmental exposure over the years caused severe deterioration of the bridge. A recent assessment indicated the basic bridge was sound and it was decided to retrofit this historic structure. Federal funding for the preservation automatically triggered a requirement for upgrading the highway loading and the seismic stabilization to modern standards. The site-specific criteria for the seismic retrofit were an estimated "maximum credible earthquake with a bed rock acceleration of 45 percent of g [6].

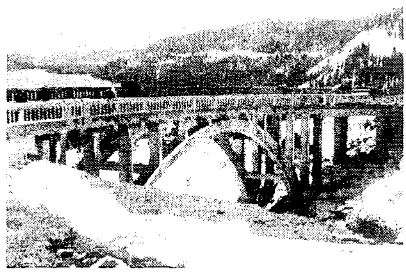

Fig. 4: Donner Summit Bridge

Expansion joints had originally segmented the bridge deck. The stabilization strategy was to make the bridge deck into a horizontal diaphragm, direct the seismic demands to the reinforced end abutments and then strengthen selected members. The modifications included:

- Closing the expansion joints and replacing the asphalted top layer with a new reinforced concrete overlay to provide a complete tie between end abutments.

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- Strengthening the end abutments and anchoring them to the granite base.
- Adding slip joints to the top and bottom of the short columns at the top of the arches.
- Rebuilding the tall columns above the spring lines of the arches with ductile reinforced column sections.
- Increasing the capacity of the arches near the spring lines by "wrapping" the arch section with a combination of steel plates and loop of high strength bars. The plates and bars were secured to the concrete with anchors drilled through the arches and the "wrapping" was covered with concrete.

6.4 Frame and infill wall buildings

The late nineteenth and early twentieth century mid-to-high-rise buildings are the heritage structures that often define the historic character of cities in California. Most of these buildings have steel or concrete frames with infill walls of unreinforced masonry or non-ductile concrete. Some of the framed buildings are braced with diagonal struts, but few are in conformance with modern standards for seismic safety.

The concern for safety often triggers a demand for seismic stabilization of these heritage buildings. The most common stabilization method is to increase the seismic resisting capacity by installing new interior concrete shear walls or by placing supplemental frames or steel bracing on the exterior facades or into the interior of the building. A newer approach is to reduce the seismic demand on the structure by using energy dissipating systems. It is based on the principle that the shaking of the ground is a form of energy and if, by some means, such as base isolation or by installing supplemental damping devices, the structure can be isolated from the ground, then the seismic demand will be reduced and the deformations controlled

6.4.1 Case study: Los Angeles City Hall, Los Angeles, California

The 32-story, 138 meter tall Los Angeles City Hall was built in 1926 before the enactment of seismic design requirements. The steel framed heritage structure has unreinforced masonry infill walls with an exterior cladding of terra cotta blocks. The terra cotta was damaged in the 1992 earthquake and it was decided to seismically stabilize the building to meet the high life safety demands for a public building. To insure integrity of the building façade in a future quake, the story drift limit for the stabilization design was established by in-situ testing of the crack formation of the terra cotta façade [7].

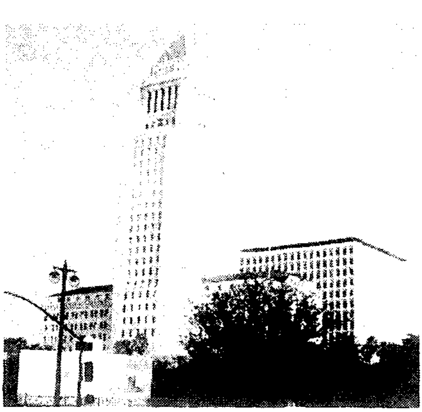

Fig. 5: Los Angeles City Hall

For the stabilization, which is to a level that exceeds any code requirement, three schemes were considered: a reinforced concrete shear wall system; a reinforced concrete shear wall with steel bracing system; and a base-isolation system with supplemental dampers. The analysis results indicated that the use of base isolation bearings in conjunction with viscous dampers at the base and the top of the building was the most effective technique for reducing inter-story drift, story shear and acceleration. The seismic stabilization program for the City Hall has required the installation of 416 high-damping rubber bearings, 90 flat slide bearings and 64 viscous dampers. The base isolation design will allow the City Hall to remain stationary while the ground during the quake moves up to 500 mm in any horizontal direction.

7 Status of Seismic Stabilization

We cannot prevent destructive earthquakes but with our present knowledge of technology we can take precautions to mitigate potential devastation. In California seismic stabilization of heritage buildings is not mandatory, but the increased concern for seismic safety and human life and a desire to protect our cultural heritage are strong incentives for improving the seismic performance of all heritage structures.

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