

# The repair and strengthening of the historic Stanford Memorial Church

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**ABSTRACT:** The Stanford Memorial Church was opened in 1903, virtually destroyed in the 1906 earthquake, rebuilt using the latest thinking in earthquake resistant design, and reopened in 1913. The church was again damaged and closed as a result of the 1989 Loma Prieta earthquake and is currently undergoing strengthening and reconstruction. The current strengthening effort uses new and existing structural elements to provide a building that will permanently protect the lives and safety of the occupants as well as the historic fabric of the church, without altering or obscuring the magnificent architectural features.

## 1 INTRODUCTION

The Memorial Church has long been one of the focal points of the Stanford Campus. Built at the turn of the century with funding from Jane Stanford, the Church occupies a central position in the Main Quadrangle of the campus and accommodates numerous activities for students, faculty and visitors to the University.

Originally built in 1903, Memorial Church suffered extensive damage in the 1906 San Francisco earthquake and was completely rebuilt in 1913 with the intent of making the new structure resistant to future earthquakes. Unfortunately, it was damaged again in the 1989 Loma Prieta earthquake and closed pending a structural review and repairs. The church has since undergone substantial analysis and design and is currently under reconstruction. It is expected to reopen in 1993.

## 2 DESCRIPTION

Memorial Church, shown in Figure 1, is built in the "Richardson Romanesque" style, similar to the oldest surviving churches near Istanbul (formerly Constantinople), Turkey. Distinctive architectural features include the rough-hewn stonework, low arches, round turrets, tile roofs and antique-looking stone carvings which are archaic in appearance. World-renowned craftsmen created the intricate stone carvings, the 25 large stained-glass windows and the 28 mosaics portraying biblical events which adorn the church.

The church has a classic cruciform shape as shown in Figure 2. The distance, end to end, from the chancel to the nave, is 190 feet, and between the transepts, 150

feet. The exterior gable wall at the nave is 86 feet tall. Second level galleries occur over each of the transepts along with an organ loft over the rear of the nave. Off the west transept is a small circular building, appropriately called the "Round Room," which is the church vestry.

The original construction was of unreinforced masonry bearing walls, with thick stone veneer and wood roofs. Of particular interest are the four, unreinforced masonry arches at each side of the crossing. They rise 86 feet high, 40 feet above the main walls of the church, and are five feet thick. They encase a steel frame which originally supported an 80-foot tall brick, stone and wood clock tower. Centered in the crossing is a steel and wood framed drum, dome and skylight of plaster and painted with religious symbols. In the pendentives of the arches are large mosaic angels, anchored to the light steel framing of the drum.

## 3 THE 1906 EARTHQUAKE

The 1906 San Francisco earthquake had a Richter magnitude of approximately 8.3 and caused extensive damage throughout the Bay Area. Located approximately 40 miles south of the epicenter, several buildings on the Stanford University campus completely or partially collapsed, including the Memorial Church, which suffered severe damage in three major areas. The clock tower partially collapsed, the roofs fell in as a result of major out-of-plane movement of the heavy unreinforced masonry and stone walls, and the front gable wall fell out due to a lack of connection to a strong roof diaphragm.

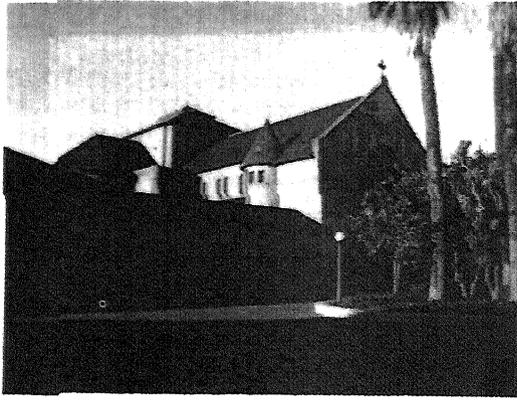


Figure 1: The Stanford Memorial Church today.

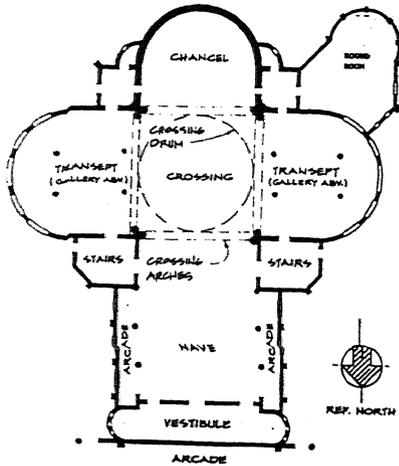


Figure 2: Floor plan.

The church underwent a thorough restoration between 1909 and 1913. The entire building, save the undamaged crossing arches and the Round Room, was dismantled to the foundation, with all the stones, windows and mosaics numbered and stored for eventual replacement (Figure 3). The building was essentially rebuilt to its pre-earthquake condition with the exception of the clock tower. The rebuilt structure included a complete vertical load carrying steel frame encased in two foot thick reinforced concrete walls around the perimeter, and straight sheathed wood roofs (Figures 4 and 6).

Since the 1913 restoration, only minor repairs and maintenance have been done on the church with the exception of the installation of a new skylight and the addition of a new organ. The new skylight was installed over the crossings, and included the reconstruction of the upper hip roof. Plywood shear panels were added to the cripple walls that support the roof and the roof was sheathed with plywood to create

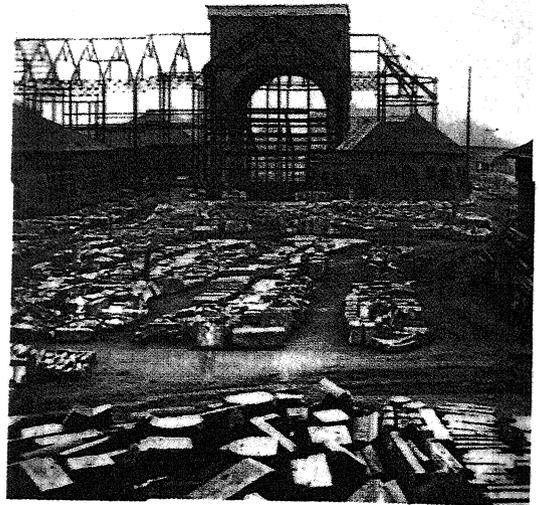


Figure 3: Restoration following the 1906 earthquake (c. 1911).

a complete diaphragm. In 1982, a new Fisk organ was added to the loft and the original Murray Harris organ relocated to the sides of the loft. This addition required the installation of a new, braced steel frame support structure designed to carry the added weight and support the front gable end wall for perpendicular seismic loads.

#### 4 THE 1989 LOMA PRIETA EARTHQUAKE

The Loma Prieta earthquake of October, 1989 was centered in the Santa Cruz Mountains, about 25 miles southwest of the Stanford campus. It measured 7.1 on the Richter Scale and had a duration of strong ground shaking lasting about 15 seconds. Stanford was subjected to about 10 seconds of 30%g intense ground shaking and damage around the campus ranged from minor to severe. Although the Loma Prieta earthquake was not the largest expected event, it did test the strengthening efforts of the 1913 restoration project.

Overall, the Memorial Church performed quite well and only suffered moderate damage. The new concrete walls, including the anchored stone veneer and stained glass windows, showed no signs of movement or distress. The Round Room was not damaged and the roofs were unaffected. Unfortunately, the worst damage was concentrated in the crossings area and forced closure of the church until repairs could be completed.

When the church was rebuilt in 1913, the new concrete walls were poured up to the columns supporting brick crossing arches, with only nominal anchorage to the arches. The arches and the unreinforced walls they support rise above the wood roofs of the church without connection and are,

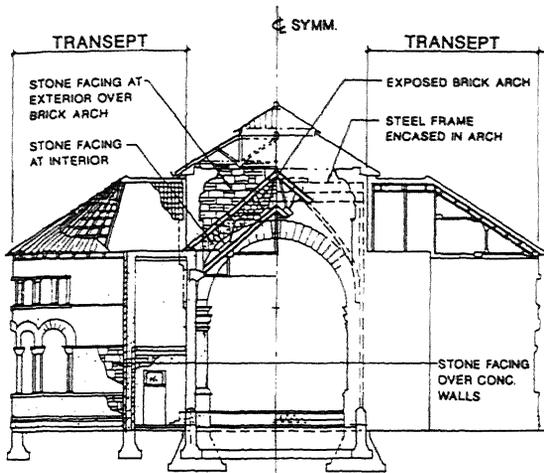


Figure 4: Elevation looking north.

therefore, completely unbraced against out-of-plane movement. In the recent earthquake, the arches suffered damage due to perpendicular movement. In the north and west arches, movement was so severe that the bedding and pointing mortar of the voussoir stones was loosened, causing several of the stones to crack and slip down as much as two inches as shown in Figure 5. Many of the unanchored ashlar stones on the face of the arches popped over an inch out from the brick, and some crumbled to the floor.

Other concentrations of damage occurred to the mosaic angels, the plaster finishes in the drum, and within the railing along the front edge of the organ loft. Because of the perpendicular movement of the arches, the upper edge of one of the mosaic angels separated from the poor quality mortar and fell as shown in Figure 7. This same movement caused numerous horizontal and vertical cracks in the finishes of the plaster drum. In addition, the stone railing in the organ loft, which was unbraced and only lightly interconnected, partially collapsed. Both the Murray Harris and Fiske Organs remained in place with only a few of the over 3,000 pipes dislodged. Fortunately, no one was hurt in the Memorial Church as a result of the earthquake.

## 5 STRUCTURAL ANALYSIS

The structural deficiencies accentuated by the Loma Prieta earthquake prompted a full structural analysis of the building. Using current techniques, H.J. Degenkolb Associates, Engineers re-analyzed the church for the expected ground shaking of a major, 1906 magnitude earthquake. During the analysis process, Degenkolb considered the expected performance of the building based on the life-safety criteria of ATC-14, and the

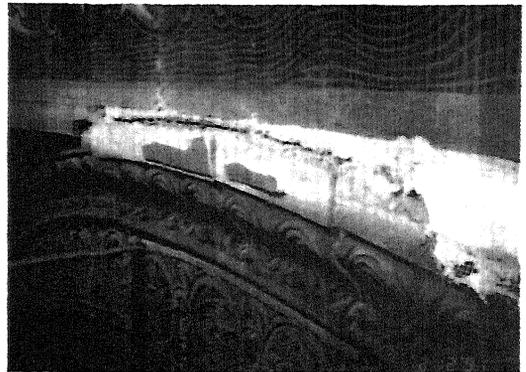


Figure 5: Damage to crossing arches (Loma Prieta earthquake).

essential buildings criteria of the California Hospital Code section of Title 24. ATC-14 sets a performance goal of only protecting life and providing safe egress after an earthquake. No consideration is given to limiting damage to the building. Title 24, on the other hand, aims at limiting damage to the extent that the building will remain essentially usable.

At this magnitude, it is expected that severe damage would occur in many elements of the church that were not sufficiently strengthened in the 1913 restoration. Because of the expected damage, the church did not meet the life-safety standard of ATC-14 and repairs and strengthening were recommended.

The most obvious deficiency in the church is the lack of sufficient in-plane and out-of-plane strength in the crossing arches and columns. The lack of any elements to brace and tie one arch to another makes the box very flimsy so that the arches can flex independently of each other and substantially speed up their deterioration under strong shaking. The existing steel frame within the arches was determined to be too weak, too flexible and not well anchored. It is expected that the arch structure would suffer substantial damage or partial collapse in the major earthquake under consideration.

The other deficiencies in the main church relate to various elements of the building. The church lacks sufficient diaphragms to interconnect the tops of the lateral resisting systems and to deliver the loads generated in the heavy roofs to the walls. None of the stone railings have sufficient strength to avoid toppling. Bracing is virtually non-existent in the original Murray-Harris organ, although it is adequate in the newer Fiske organ.

The unreinforced masonry Round Room has large window openings and relatively narrow piers. The roof is constructed of large trusses bearing on the walls and supporting a straight sheathed diaphragm. The roof transitions from a conical shape to a straight slope creating a poor load path at the valley framing. The piers lack both the in-plane and out-of-plane strength to

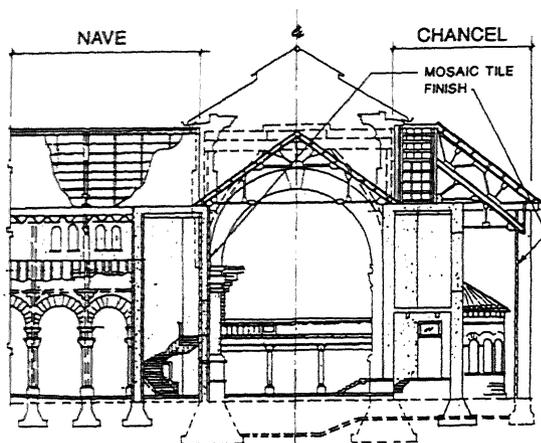


Figure 6: Elevation looking east.

carry tributary seismic loads to the foundation and the roof is incapable of delivering the lateral load, as a cantilever, back to the main church walls.

Several elements of the church, however, were well designed in the 1913 reconstruction and remain as a useful part of the lateral system. The numerous exterior concrete walls form a complete longitudinal and transverse shear wall bracing system. The extent of the walls reduces the tributary loads on each, and walls in one direction help to brace those perpendicular. The vertical steel frame provides an independent vertical load-carrying system and the needed trim steel around many of the window and door openings. In modern terms, the church has a dual lateral force resisting system.

It appears that the reconstruction engineers of the early 1900's clearly understood the earthquake resistance of a steel frame/concrete shear wall structure. Their observations form the 1906 earthquake were likely their best teacher. Unfortunately, they had yet to develop a basic understanding of how lateral forces are generated within a structure and how they were resisted. Today, we know that seismic forces are generated in the masses of a building and transferred to the various resisting elements based on the rigidity of those elements and their interconnection. These transfers require sufficiently strong and ductile diaphragms, chords and collectors to interconnect the various lateral force resisting elements of the building.

## 6 THE PRESENT STRENGTHENING

Based on the analysis of the existing structural system, Degenkolb developed two schemes to restore and enhance the strength of the church. The first and minimum acceptable scheme was aimed at strengthening the church so that it would comply with

the life-safety standard of ATC-14. First and foremost, the University wanted to repair and strengthen the church so that it would have a reasonable chance of protecting the lives of the people inside during a major earthquake. The second level of strengthening was aimed at minimizing damage as much as possible to permanently preserve the historic character and fabric of the church. The design criteria for the second level went beyond life-safety to a "building integrity" level and was based on the Hospital Code sections of California's Title 24.

Because of the unique characteristics of the church, the key differences between the two strengthening schemes were in the level of strength to be built into the lateral system and the interconnections, and the use of unreinforced masonry to carry vertical or lateral loads. ATC-14, as a life-safety criteria, permits the use of unreinforced masonry at low stress levels and requires a smaller design lateral strength. Title 24 on the other hand, requires that the building be designed to sustain loads almost twice as large as ATC-14 and does not permit the use of unreinforced masonry.

The cost estimate to achieve the life-safety level of strengthening totaled approximately 5 million dollars. The cost estimate to achieve the building integrity level of strengthening was approximately 15.5 million dollars. The difference in cost included .6 million dollars related to the increase in strength and 9.9 million for the removal and replacement of the unreinforced masonry arches, and the reconstruction of the Round Room. The University elected to implement a middle solution that used the higher lateral forces and retained the unreinforced masonry. It is expected that this solution will not only provide life-safety, but also substantially protect the historic character and fabric of the church during the strengthening process and after the next major earthquake. Some significant damage is expected to occur in the remaining unreinforced masonry elements.

During the development of the strengthening details, every effort was made to preserve the historic fabric of the church and the existing architectural features. Special concern was given to developing strengthening measures for both levels that could either be done from behind existing visible elements or in a way that would allow these elements to be temporarily removed and replaced without altering their appearance.

The major thrust of the strengthening occurred in the crossing. The four large arches needed to be braced against out-of-plane movement and substantially connected to the perimeter concrete shear walls. The resulting details are shown in Figure 10. During exploration of the existing construction, a 20-inch void space was discovered within the five-foot thick arches containing the steel frame which had originally supported the clock tower above. This void space around the full perimeter of the crossing provided an excellent opportunity to strengthen the arches from

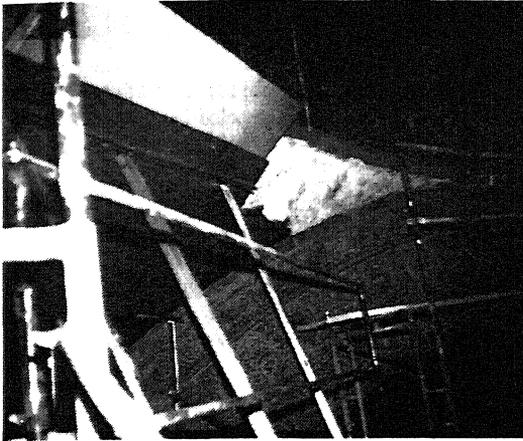


Figure 7: Damaged wing of mosaic angle.



Figure 9: Bracing of balustrade railing at organ loft.

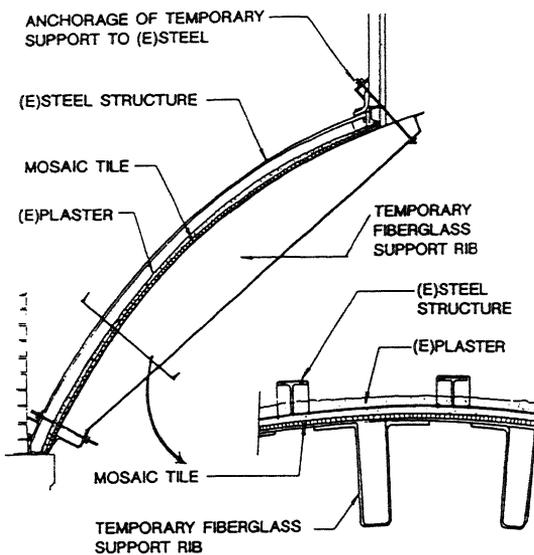


Figure 8: Temporary support of mosaic angles.

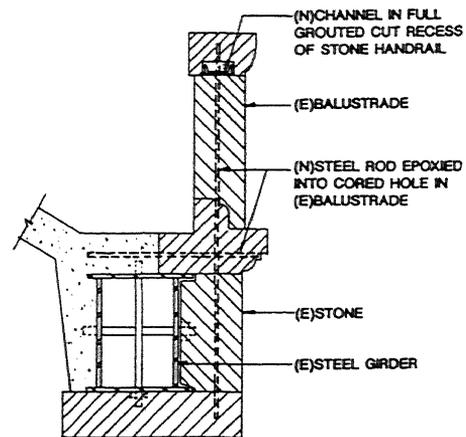


Figure 10: Exploded view at crossing arches.

within. By removing a selected amount of brick from the interior wall of each arch, a complete, reinforced concrete wall was designed within the void space to interconnect the arch structure, provide the needed out-of-plane strength for the perpendicular loads, and substantially enhance the in-plane strength. To complete the perpendicular bracing of the arches, a concrete and steel bracing structure was added to the top of the arches that would work with the existing steel framing to transfer the seismic loads to the available shear walls.

To substantially connect the crossing to the adjacent shear walls, large steel collectors were installed the arches and the top of abutting concrete walls of the church. The collectors had to penetrate the steel corner

columns of the arches and connect to the available gusset plate system. The collectors were welded to the existing steel frames within the tower, doweled to the abutting walls, and completely encased in the concrete.

To strengthen the roof level diaphragms, the straight sheathing on the roofs over the entire church, including the Round Room, was removed and replaced with plywood. The in-plane tension capacity of the roof was enhanced by strengthening the existing splices between the purlins and providing a substantial connection to the end walls of each diaphragm. Each plywood roof diaphragms was anchored to its supporting shear wall with a new concrete cap beam, mud sill, anchor bolts and blocking.

With the bracing of the arches and their anchorage to the main building, the mosaic angels, drum and dome features in the crossings are expected to be protected damage due to major structural movement. However, because of the poor bonding mortar between the tile

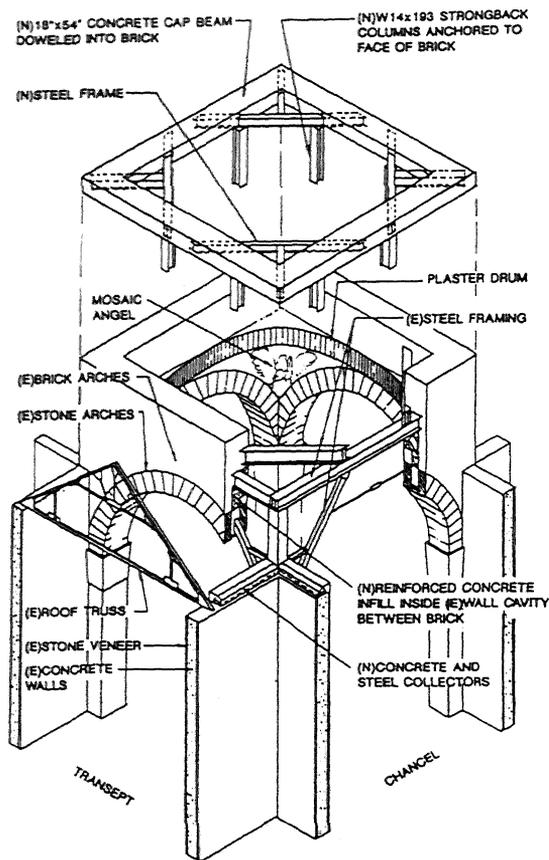


Figure 11: Detail of balustrade railing.

and the backing, there was still a concern for the stability of the mosaics during a major earthquake. For safety and preservation of this artwork, the University decided to remove the existing poor quality mortar and replace it with a fiberglass resin based anchorage system. To avoid a potential \$2 million cost to take down the angels, perform the work and put them back up, and to preserve the work in its original condition, fiberglass molds were cast against the fronts of the angels, held securely in place with anchors to the steel frame, so that the original backing material could be removed and replaced from behind. The details of this unique restoration procedure are shown in Figure 8.

The railings in the galleries and the organ loft were braced by adding reinforcing within each baluster and the stone cap. The railings were carefully dismantled and cored to permit the installation of dowels and steel cap channel or plate as required. The dowels were epoxied into the concrete walls beneath the railing. A typical detail of this strengthening is shown in Figures 9 and 11.

Finally, various incidental bracing details were instituted to abate as much as possible areas that could

experience damage. The original Murray-Harris organ was braced with steel and wood to prevent the organ and the pipes from falling out into the nave or stair towers. Bracing was applied to the supporting platform for the organ and to the pipe enclosures. In addition, a small parapet near the Round Room was braced and four small concrete diaphragms were strengthened and the large chandeliers were provided with a second line of vertical support.

The seismic strengthening of the Stanford Memorial Church stands as a notable example of combining historic preservation with seismic strengthening. The project was unique because of the 1913 reconstruction work and the availability of "behind the finishes" locations to work. It is to Stanford's credit that they pursued a historically-sensitive repair and strengthening of this facility which the design team and contractors carried out in a balanced manner.

Owner:	Stanford University
Structural Engineer:	H.J. Degenkolb Associates, Engineers
Architect:	Hardy, Holzman, Pfeiffer Associates
Conservator:	Leslie Bone
General Contractor:	TBI/Dinwiddie Construction