Giorgio Croci

Emergency Stabilization of the Basilica of St. Francis of Assisi

This paper describes the damage caused by the 1997 earthquakes and aftershocks to the Basilica of St. Francis of Assisi and the urgent measures executed to stabilize the structure. The studies utilizing many mathematical models and analyses to design the seismic retrofit and restoration will be presented in a paper in a second disaster preparedness issue of *CRM* scheduled for publication next year.

History, Damage, and Collapse

Many earthquakes have shaken the Basilica of St. Francis since its construction in the 13th century. Major earthquakes occurred in 1279, 1328, 1703, 1747, 1781, 1799, 1832, 1859, 1917, and 1979. Yet none of these produced damage as great as that which hit central Italy during the night of September 26, 1999, as well as the second earthquake that struck the basilica at 11:42 a.m. Damage consisted of the destruction of the vaults close to the façade and those close to the transept and a portion of the left transept. The earthquake also caused large cracks and permanent deformation over all of the vaults of the basilica, leaving them in a very precarious and dangerous condition.

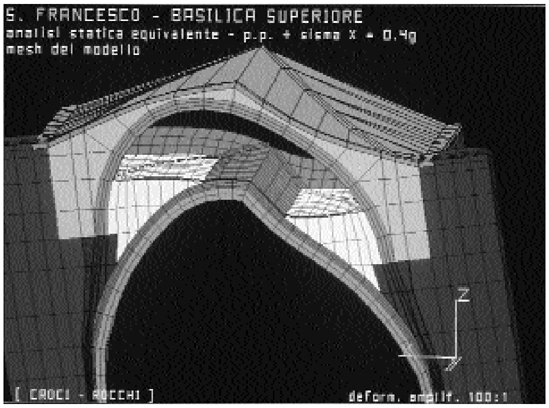
Besides the differing impact that the many historic earthquakes of different characteristics may have produced on the basilica, other factors have increased the vulnerability with respect to the past. Concerning the tympanum, constructed of a cavity wall with two faces and an inner fill, the cause of the partial collapse was the deterioration of the mortar which connects the stones of the external face with the inner fill (the first damage was produced on September 26, but it was the quake of October 7 which created a large hole in the wall). The reduced cohesion and bonding of the deteriorated mortar resulted in progressive failure of the wall stone by stone.

Damage in the tympanum on October 7, 1997.

Concerning the vaults, the collapse was produced by a large volume of fill which was mainly broken roofing tiles and other loose materials accumulated over centuries of roof repairs in the springer zones. During earthquakes, this non-cohesive fill alternatively acts only in one direction because there is no connection in the opposite direction. In addition, the loose fill follows the movement of the vaults, opposing their recovery and facilitating increasing permanent deformations. When the quake of September 26 hit the basilica, it is very likely that there was already some permanent deformation, reducing the curvature and, therefore, the bearing capacity as the result of previous earthquakes.

The fill accumulated through the centuries over the vaults.

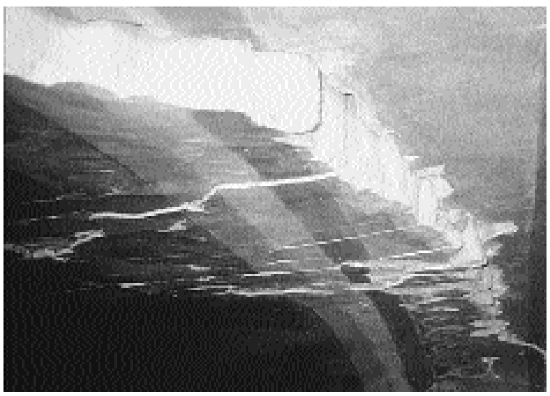
The failure mechanism of the vaults close to the façade, filmed by Umbria Television, resulted from the progressive loss of curvature of the ribs, then a "hinge" was produced in the middle and finally the rib collapsed, drawing the vault down



Deformations of the vaults produced by the fill.

with it. A similar mechanism occurred in the zone close to the transept, where the second vault collapsed.

The collapses were concentrated in these specific zones because, as the direction of the seismic force was mainly perpendicular to the nave axis, the system of the vaults behaved globally like a "beam," where a kind of restraint at the ends was provided by the stiffness of the façade and the transept. This behaviour is clearly shown by the global mathematical model that will be presented in the next *CRM* issue on disaster preparedness.



Large cracks in the vaults with relative movements of around 25 cm.

Urgent Measures

Urgent measures (emergency stabilization) were required immediately after the earthquake to prevent the total collapse of the tympanum and the vaults.

The Vaults. The surviving vaults were damaged by large cracks distributed on both the intrados (interior face of the vault) and the extrados (exterior face of the vault). The curvature, as already said, was reduced in several areas.

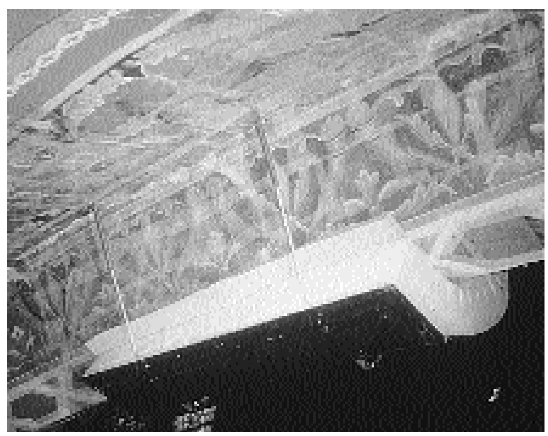
The danger that the vaults might collapse, and the consequent risk to human life, precluded the possibility of supporting the vaults from the ground level. Rather, a platform was suspended from the roof above the vaults with the double function of inspecting and providing a base for working over the vaults.

The urgent measures taken in the first month after the main earthquake can be synthesized as follows:

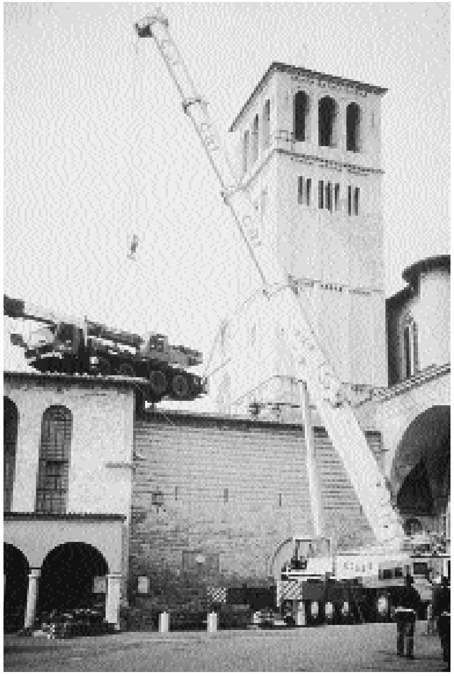
- Removing the huge load of the fill in the springer zones of the vaults;
- Filling the cracks with a salt-free mortar to limit possible damage to the frescoes, first taking the precaution of inserting a strip of polyurethane in the larger cracks to prevent the mortar from flowing out;

Cracks and loss of curvature of the ribs.

- Applying bands of synthetic fibres over the cracks of the extrados;
- Suspending the vaults from the roof framing with a system of tie bars, having first inserted two springs to maintain the force at the design value, independent of thermal effects and minor vibrations; and
- Suspending the ribs from the roof with a system similar to the previous one after having placed a kind of steel cradle filled with soft rubber underneath in order not to damage the frescoes.



Suspension of the deformed kerbs (restraining straps) to the roof.



A crane in front of the convent lifts a second crane over the wall into the courtyard.

The Tympanum. The risk was that if the tympanum were to collapse it would destroy the roof of the chapel below, causing the loss of frescoes and works of art of inestimable value. After long reflection, it was decided to use a huge crane, 50 meters tall.

But such a crane could not pass through the narrow gate into the inner courtyard. This problem was solved using two cranes. The first crane located outside the basilica complex lifted the second crane over the roof of the building and deposited it in the inner courtyard.

Organizing this operation involved anchoring two cantilever steel trusses on the two walls of the transept. The trusses were designed to support a 4.5-ton steel-frame structure in the shape of the tympanum, a triangle 8 meters high and 17 meters wide at the base.

The following emergency stabilization work was completed between October 10-14, 1997. The steel structures were built; two cranes arrived on the square in front of the basilica; the first crane lifted the second one into the courtyard; the two cantilever steel trusses were lifted over the roof of the transept and were anchored to the lateral walls, ready to receive the steel frame.

After some attempts hindered by heavy rain and wind, the crane succeeded in lifting the steel tympanum over the brackets. The following day the empty spaces and larger holes were filled with polyurethane foam to provisionally stabilize the masonry.

Once the urgent measures were completed and the structure relatively stable to prevent additional damage from continuing aftershock, the damaged basilica was studied and analized using mathematical models and the seismic retrofit and restoration was designed and executed. The second part of this article will appear in a future issue of *CRM* on disaster preparedness.

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Lisa Usman

Mitigation— Fact or Fiction?

Most of our knowledge relating to seismic activity has come about in the last 30 years. This is a fraction of time considering earthquakes have been a fact of life for man as long as history has been recorded. It is only since the late 1960s that the theory of plate tectonics was fully understood and recognised as being the most common cause of earthquakes. The question is, "Are we using this information to the best of our ability, or are we merely information gathering?"

While the cause of seismic activity may not have been known, attempts to construct buildings able to withstand the "shaking of the ground" have been discovered dating back to the Roman Empire. Excavations at the Greek towns of Sardis and Magnesia, almost totally destroyed in an earthquake and rebuilt with the assistance of Rome, revealed unusual foundations. Structures were found with a grid of wooden beams at the foundation level and archeologists believe this may be the first attempt to construct earthquake-resistant buildings.[1]

Understanding what causes earthquakes makes it possible to predict with considerable accuracy where they might occur, even if we are not able to ascertain when they might happen. We also have a clear idea of the type of building that probably will and will not withstand an earthquake. With this information it should be possible to substantially reduce vulnerability of both people and buildings. If an attempt is to be