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Restoring the Basilica of St. Francis of Assisi

The Basilica of St Francis in Assisi was severely damaged by earthquakes and aftershocks in September and early October 1997. After emergency measures had stabilized the structure (see *CRM* 23:6, 2000), a detailed monitoring and mathematical modelling study was carried out. This paper reports on these processes.

Seismic Forces and Mathematical Models

On September 26, 1997, the ground acceleration close to the basilica measured about 0.16g[1] in the direction of the longitudinal axis of the basilica nave and about 0.18g in the direction perpendicular to the nave. Considering a reasonable amplification factor for the vertical structures, it is likely that the top of the structure reached a transversal acceleration of around 0.36g.

Expected major earthquakes for the Assisi area are at least 1.5 times stronger than the earthquake of September 26, 1997. Moreover, the basilica nave and the monastery are located on a hill oriented in an east-west direction. In the north-south direction the nave is very tall and narrow which provides little resistance to seismic forces. This results in local amplifications and acceleration in case of north-south seismic forces larger than that in the center of the city of Assisi. These considerations bring us to take into account a possible maximum ground acceleration of around 0.3 to 0.35 g, in the perpendicular direction with respect to the basilica nave (longitudinal axis).

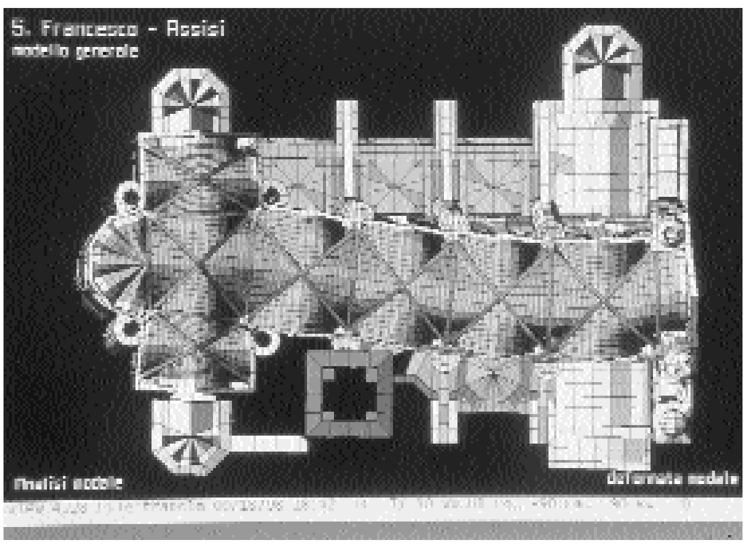
The measurements taken on occasion of the numerous seismic events during 1998, show transversal acceleration at the top of the vaults from 3 to 8 times larger than those on the ground. These amplifications are much larger than that evaluated for the September 26 earthquake; therefore, two things must be considered: during stronger earthquakes, when parts of the structure exceeds the elastic limit, there is major energy dispersion and therefore the amplification is reduced; and the removal of the fill in the springer zones, as carried out as part of the emergency stabilization, increases the local amplification of the vaults.

On the basis of the previous considerations, and also considering the present damaged state of the vaults, it is prudent to take into account dynamic amplification (from the ground up to the top of the vaults) to a magnitude of four times. Based on this, the design for the reinforcements for horizontal transversal acceleration, at the level of the vaults, assumed an acceleration of 1.2 to 1.4g.

Structural Analysis

Various mathematical models have been prepared to study the structural behaviour under the worst scenario, the effect of seismic forces perpendicular to the axis of the basilica. The general model of the basilica shows that, in addition to the local effects due to the fill, the vaults close to the façade and the transept take supplementary stress caused by the restraint produced by façade and transept.

The model of a central module of the nave with the fill (situation before September 1997)



One of the modes of vibration of the global model.

clearly shows that high tensile stress is produced in the ribs and the curvature is reduced even in static conditions under the effect of dead loads. A preliminary step-by-step analysis with horizontal statically equivalent forces shows that when seismic forces reach approximately 0.18g, cracks and permanent deformation occurs, and that with forces between 0.25 and 0.30g the vault may collapse. These values of the seismic forces are comparable with the values induced by the earthquakes of September 1997. The values also explain the great damage everywhere and how the vaults near the façade and near the transept, which received the additional stress, collapsed.

The model of a central module of the nave, without the fill refers to the deformed shape of the vaults, as it has been surveyed; however, it neglects the stress accumulated as a consequence of deformations. This approximation is partially justified by the presence of the cracks, but it would be impossible to evaluate this stress reliably. A first elastic analysis shows that stresses are significantly reduced after the removal of the fill. Considering horizontal statically equivalent forces, a second step-by-step analysis shows that great deformation develops when the horizontal seismic force on the vaults reaches approximately 0.4g (compared to 0.18g with fill). Collapse occurs between 0.6 and 0.7g (instead of 0.25g to 0.3 g with fill). This improvement, however, is not sufficient to deal with the maximum expected earthquake.

A step-by-step analysis of the model of the reinforced vault, taking into account the reinforcement ribs connected with the extrados of the vaults, shows that deformation is greatly reduced and the vault's behaviour is largely improved. When the horizontal statically equivalent force reaches the design value of 1.2g the stress in the reinforcements reaches half of the strength. The mathematical model also shows that large partialisations and deformations of the vaults occur only when the horizontal acceleration reaches 1.6g.

Research and Testing

The problem of the definitive restoration and consolidation of the basilica was complex. Because of the presence of the frescoes it was impossible to reduce the deformation and to reestablish an adequate curvature and autonomous bearing capacity. Different solutions were modelled to decide how to best strengthen the vaults and secure their stability over time, without creating a risk to the frescoes and without compromising the historical value of the original vault's structure. The option of building a reinforced concrete shell or reinforced concrete ribs on the extrados, was rejected *a priori*, as too heavy and incompatible with the historical value of the monument. The use of steel ribs was rejected as well because of the difficulty to follow the deformed shape of the vaults and, consequently, to obtain a continuous connection between ribs and vaults.

The solution chosen was to use composite materials to create a series of thin little ribs following a pattern typical of Gothic structures on the vault's extrados, leaving the original structure clearly visible. These ribs are built in situ, so that it is possible to follow the deformed shape of the vaults; while the width of the ribs remains constant, the height may then change in relation to the deformation of the vaults. In essence, the extrados of the ribs can follow a regular curve parallel to the original ideal surface of the undeformed vaults.

The ribs are made of aramid fibres bedded in epoxy resins around a central timber nucleus. These fibres are light but very strong.[2]

Samples of the constituent materials and of the composite ribs have been tested. As of 1997, there had been not much experience on the application of these products to consolidate historic masonry structures. The tests allowed refinement of the design of the ribs to improve their mechanical characteristics and to reduce their section to a minimum. The strength of the ribs was increased by inserting unidirectional aramid fibre bars in the intrados. Unidirectional glass fibre bars were inserted in the extrados because glass fibres have higher performance under compression stress.

The decision to utilize a central nucleus was made because this guarantees higher resistance and energy dissipation and prevents any buckling of the thin webs of aramidic fabric. In addition, the ribs could be built faster with a central nucleus.

Several different materials were tested for the nucleus: rigid foams, different types of wood, and composites of wood plus foam. Mahogany nautical plywood was chosen stratifying several layers of plywood each over the other. The use of cross-directional plywood, instead of layers of simple wood, reduces the transversal core expansion under load action. Very homogeneous mahogany wood guarantees high resistance and stiffness to compression while the nautical treatment, according to the strictest standards, results in a wood of high durability and very resistant to decay. The wooden layers, glued on site, permit following the deformed shape of the vaults.

Pull tests were performed to verify the adhesive capacity between composite elements and masonry both in the case of direct gluing and through aramid fibre pivots. Cyclical tests have shown good conservation of bearing capacity beyond the yield point with good ductile behavior.

Reinforcement of the Vaults

The strengthening of the vaults consists of the new ribs connected at the extrados; the anchorage of the ribs at the roof; the grouting of the cracks; the connection of the arches, which support the roof, to the perimetral walls; and the steel beam placed in the nave over the cornice of the walls.

The Ribs

The rib pattern consists of:

- a couple of ribs placed parallel to the transversal arches, the most sensitive and weak in an earthquake because of their reduced or missed curvature
- a series of ribs placed just over the diagonal arches
- smaller ribs placed over the webs
- longitudinal ribs placed on the vault crowns and at mid height of the vaults

These ribs are fabricated in place in layers of various materials. The construction phases are:

- On the vault extrados surface, after an adequate cleaning, the first four-directional (0°, ±45°, 90° angle ply) tissue of aramid fibre of 230gr/m^2 is glued using epoxy resin.
- Over this first layer, the pultruded[3] flat aramid fibre bars are glued and covered by a second tissue of aramid fibres.
- Subsequent strata of mahogany plywood layers are placed to create the rib core.
- The wooden core is then covered by a third four-directional aramid fibre tissue 360gr/m^2, heavier than the previous ones, as it is expected to be part of the stratification of the composite lateral walls of the rib.
- At this point, the pultruding flat fibre glass bars are glued.
- Finally, everything is covered with another four-directional aramid fibre tissue of 360gr/m^2.

Anchoring the Ribs

The ribs are connected to a system of tie bars, which are anchored to the roof. Each tie bar includes a spring, similar to the solution adopted for emergency stabilization measures. This reinforcement reduces the deformation under seismic forces.

Grouting the Vaults

The reinforcement of the vault's cracked structure, where continuity has been compromised, has been created using a specifically formulated mortar. This mortar is salt-free and compatible with the frescoes, sufficiently fluid to penetrate into all the cracks and micro-cracks; capable of being injected in dry masonry (no use of water is allowed), and possesses good strength and bond capacity establishing structural continuity through the cracks.

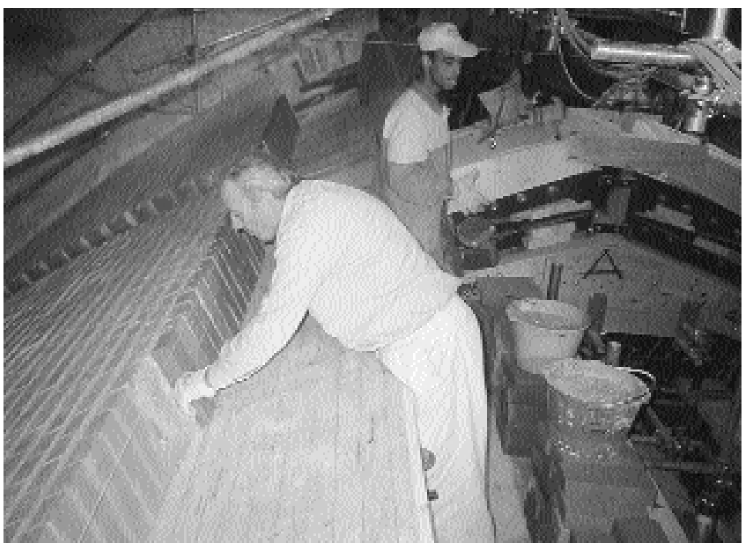
Anchoring the Main Arches

The masonry arches supporting the roof stand on little vaults, which are situated over the springers of the main vaults without any structural connection and with a certain eccentricity with respect to the main pillars. Therefore, it was decided to anchor the base of the arches at the walls and the towers behind them, which in this very peculiar Italian Gothic structure, have the function of abutments. The anchoring consists of a steel belt and pre-stressed horizontal bars.

Trussed Beam

Over the centuries, the frescoes on the walls have frequently suffered damage and cracks due to the deformation caused by earthquakes, even if, fortunately, the wall resisted and never collapsed. To limit this phenomenon, a horizontal

The reconstruction of the vault.



The cylinders that contain the special anchorages connecting the tympanum and the roof.

steel trussed beam has been placed over the cornice of the walls inside the basilica (immediately below the stained glass windows), to stiffen and strengthen the walls covered with Giotto's frescoes. The connection between this beam, which runs along the perimeter, and the walls has been created with special viscous devices which allow relative displacements due to thermal effects, but become rigid under dynamic forces and provide full strength in the event of earthquakes (shock transmitter).

Reconstructing the Vaults

The reconstruction of the collapsed vaults was a major problem. Fortunately, after painstaking research, several frescoed bricks were identified that could be re-used to re-build the vaults.

The operation has been particularly successful with regard to the pieces of ribs, which have maintained a good bond between the bricks, forming voussoir-like elements, even though they fell 25 meters. In the laboratory it was possible to re-assemble the broken parts of ribs in such a way as to create voussoirs 40 to 60 cm long. These voussoirs were then placed on a provisional centering to rebuild the ribs.

It has not been possible, on the other hand, to recover significant elements of the webs, so that new bricks, especially made to have the same substance and similar characteristics of the originals, had to be used. The reconstruction of the vaults took into account the problem of re-establishing not only a structural, but also a stress continuity between the new and the original portions of the vaults. To compensate the deformation, including the shrinkage of the mortar, and to calibrate stress distribution, a system of jacks was placed in a provisional joint on the crown of the new vaults.

Reconstructing the Tympana

The restoration of the basilica was completed with the reconstruction of the collapsed portion of the left tympanum and the removal of the deformation that both the transept tympana suffered. Stones from the original quarry were used.

To reduce seismic forces transmitted to these tympana, which although consolidated remain delicate structures, the connection between it and the roof was created interposing special steel devices, composed of shape memory alloy, able to dissipate a certain amount of energy.

Conclusions

The operations to save and then to consolidate and restore the Basilica of St Francis of Assisi have all followed the same philosophy:
(1) to place the most up-to-date techniques and technologies at the service of culture in order to respect the historic value of the ancient building and (2) to obtain adequate safety levels while changing as little as possible the original design. Some of these technologies, never applied before in the field of restoration, were studied specifically for this occasion, offering new and interesting possibilities for the safeguarding of our architectural heritage.

Notes

1 g being equal to the force of gravity.

2 The tensile strength of the aramid fibre used is 30,000 kg/cm2 and that of the fibre with resin is about 14,000 kg/cm2. It is less stiff than steel, the elasticity modulus of the fibre being 1,200,000 kg/cm2 and that of the fibres with resin 600,000 kg/cm2.

3 Pultrusion is a manufacturing process for producing continuous lengths of reinforced plastic structural shapes with constant cross-sections.

4 The study and the project have been prepared in collaboration with architect Paolo Rocchi, and the participation of engineer G. Carluccio, under the supervision of Dr. Antonio Paolucci, the artistic co-ordinator of the Ministry of Cultural Heritage, architect Costantino Centroni, superintendent of Umbria and Dr. Giuseppe Basile, of the Italian Institute of Restoration and frescoes expert. The mathematical models have been prepared with the cooperation of engineer Fabio Sabbadini, engineer Alessandra Carriero, engineer Marco Losappio and Architect Herzalla Aymen. engineer Alberto Viskovic has also participated in the testing of the new materials and the design of the reinforcements.

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Illustrations by the author.