THE RESTORATION OF THE BASILICA OF ST FRANCIS OF ASSISI

Giorgio Croci *

1. History, damage and collapse

In its history many earthquakes have hit the Basilica of St Francis, which was built in the 13th century. Important earthquakes occurred in 1279, 1328, 1703, 1747, 1781, 1799, 1832, 1859, 1917, 1979, and yet none produced damage as great as that which hit central Italy during the night of September 26, 1999, as well as the second that struck the Basilica at 11,42 a.m. The result was the destruction of the vaults close to the façade, of those close to the transept, of a portion of the left transept and the production of large cracks and permanent deformation all over the vaults of the Basilica, leaving them in a very precarious and dangerous condition.

Besides the differing impact that the earthquakes of different characteristics, which followed each other during the centuries, may have produced on the Basilica, other factors have increased the vulnerability with respect to the past.

As regards the tympanum, constructed of a cavity wall with two faces and an inner fill, the cause of the partial collapse was the decay 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 could not prevent single stone blocks from progressively detaching each from the other and falling.

As regards the vaults, the collapse was produced by a large volume of fill which was mainly broken tiles and other loose materials accumulated over centuries of roof repairs in the springer zones. During seismic activity, this fill, without any cohesion, alternatively acts only on one side, whilst on the other side the fill is detached. What is more, the lose 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 permanent deformation, reducing the curvature and therefore the bearing capacity, was already present, having been progressively produced and increased during the previous earthquakes.

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 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 below.

2. Urgent measures

Urgent measures were required immediately after the earthquake so as to prevent the total collapse of the tympanum and of the vaults.

a) The Vaults

The surviving vaults were all affected by large cracks distributed both on the intrados and the extrados; curvature, as already said, was lost 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 consist on removing the huge load represented by the fill in the springer zones of the vaults, applying bands of synthetic fibres over the cracks of the extrados and suspending the vaults from the roof 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.

b) The Tympanum

The risk was that if the tympanum were to collapse it would have destroyed 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 m tall.

But such a crane could not get through the narrow gate into the inner yard. This problem was solved by using two cranes; one first outside the Basilica complex lifted the second one over the roof of the building and deposited it in the inner courtyard.

When the crane was in the yard it lifted a provisional steel structure orgainst the damaged tympanum to prevent any collapse.

3. Seismic forces and mathematical models

The acceleration measured on Sept. 26, 1997, at the ground close to the Basilica, was about 0,16g in the direction of the longitudinal axis and about 0,18g in the perpendicular direction. 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.

Different mathematical models have been prepared to study the structural behaviour under the effect of seismic forces perpendicular to the axis of the Basilica (which is the worst possibility);

The General Model of the Basilica this shows that the vaults close to the façade and the transept take, in addition to the local effects due to the fill, supplementary stresses due to the restraint produced by the façade and the transept.

The model of the vault with the fill (situation before Sept. 97) has clearly shown 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 around 0.18g, cracks and permanent deformation is produced, and that with forces between 0.25÷0.3g the vault may collapse.

These values of the seismic forces are comparable with the values induced by the earthquakes of September 1997 and explain the great damage everywhere and how the vaults near the façade and near the transept, which received the additional stress, collapsed.

Finally has been analysed a model of the reinforced vault (re below) which shows that deformation is reduced greatly and the vaults' behaviour is largely improved.

4. The reinforcements of the vaults

The strengthening of the vaults consists of five main parts: 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; the steel beam placed in the nave over the cornice of the walls.

a) The Ribs

The vault have been reinforced placing on the extrados a series of ribs whose pattern is indicated.

The ribs are made of aramidic fibers bedded in epoxy resins around a central timber nucleus. Several laboratory tests have been made (Fig. 14); the strength of these fiber is much larger than the steal and reaches 14.000 kg/cm^2.

b) The Ties Bars to Anchor 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 urgent measures. This reinforcement aims to reduce the deformability under seismic forces.

c) The Grouting of the Vaults

The reinforcement of the vaults' cracked structure, where continuity has been compromised, has been created using a mortar capable of satisfying very specific and severe unusual conditions. This mortar, chosen after long study and research, is salt-free and compatible with the frescoes; sufficiently fluid to penetrate and diffuse to all the cracks and microcracks, capable of being injected in dry masonry (no use of water is allowed) and having good strength and bond capacity so that a structural continuity through the cracks may be established;

d) Belts to Anchor the Main Arches

The masonry arches, which support the roof, stand simply 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 has been 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 has been realized with a steel belt and prestressed horizontal bars ;

e) The Trussed Beam

During the centuries, the frescoes on the walls have frequently suffered damage and cracks due to the deformation produced by earthquakes, even if, fortunately, the wall resisted and never collapsed. To limit this phenomenon, a horizontal steel trussed beam has been placed over the cornice of the walls inside the Basilica (immediately below the stainglass 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)

5. Reconstruction

a) The Vaults

The reconstruction of the collapsed vaults has been another major problem. Fortunately, after a painstaking piece of research, several frescoed bricks that could be reused to rebuild the vaults have been identified.

The operation has been particularly successful as regards the pieces of ribs, although having fallen down 25 metres, they have maintained a good bend between the bricks.

It has, therefore, been possible to assemble in the laboratory, the broken parts of ribs in such a way as to create a sort of voussoirs about 40 - 60 cm long. These voussoirs are then placed on a provisional centring to rebuild the ribs .

It hasn't 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 original ones, will be used.

The problem of the frescoes is going to be solved reutilizing most of the pieces that has been possible to recover, even if it impossible to recreate the figures and geometry as they where.

b) The Tympanums

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 tympanums suffered. Stones from the same original quarry were used.

To reduce seismic forces transmitted to these tympanums, 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.

6. Conclusions

The operations carried out, firstly to save and then to consolidate and restore the Basilica of St Francis of Assisi, have all followed the same philosophy: 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 to obtain adequate safety levels whilst changing as little as possible the original conception. Some of these technologies, never applied before in the field of restoration, have been studied specifically for this occasion, offering new and interesting possibilities for the safeguarding of our architectural heritage.

7. Acknowledgements

The study and the project has been prepared in collaboration with Prof. Arch. Paolo Rocchi, and the participation of Eng. G. Carluccio, under the supervision of Dr. Antonio Paolucci, the artistic co-ordinator of the Ministry of Cultural Heritage, Arch. 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 co-operation of Eng. Fabio Sabbadini, Eng. Alessandra Carriero, Eng. Marco Losappio and Arch. Herzalla Aymen. Eng. Alberto Viskovic has also participated in the testing of the new materials and the design of the reinforcements.

*** Girogio Croci**

Born in Rome on March 1936, Giorgio Croci is currently Professor of Structural Engineering and holds the chair of Structural Restoration of Monuments and Historic Buildings in the Faculty of Engineering of Rome "La Sapienza" University.
He is a consultant to UNESCO, ICCROM, Council of Europe, the Italian Ministry of Foreign Affairs, and the Ministry of Cultural Heritage and he has carried out important research, studies and projects for the strengthening and restoration of historical buildings, such as the Coliseum, the Basilica of St. Francis of Assisi, the Tower of Pisa, the Pyramid of Chefren, the Temples of Angkor, Hagia Sophia in Istanbul, the Roman Temples of Baalbek in Lebanon, the Konarek temple in India, the Tilal Kari Mosque in Samarkand, etc.