

THE SACRED CONVENT AND THE BASILICA OF ST. FRANCIS OF ASSISI

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One of the most impressive and richest religious places in art in all of Italy is surely the basilica of St. Francis of Assisi. It consists of an entity organised in a building complex which compose the architectonic structure of the Sacred Convent which arose around the mass of the two superimposed churches over various centuries.

The building of the Lower Church began in 1228, two years after the death of the Saint (1186-1226); in 1230 it was ready to receive the corpse of St. Francis and also the great bell-tower with its typical Lombard Romanesque forms must have been completed in 1239.

The building work advanced rapidly under the direction of Friar Elias who completed the Lower Church in Romanesque style with mighty and solid structures in gentle half-light.

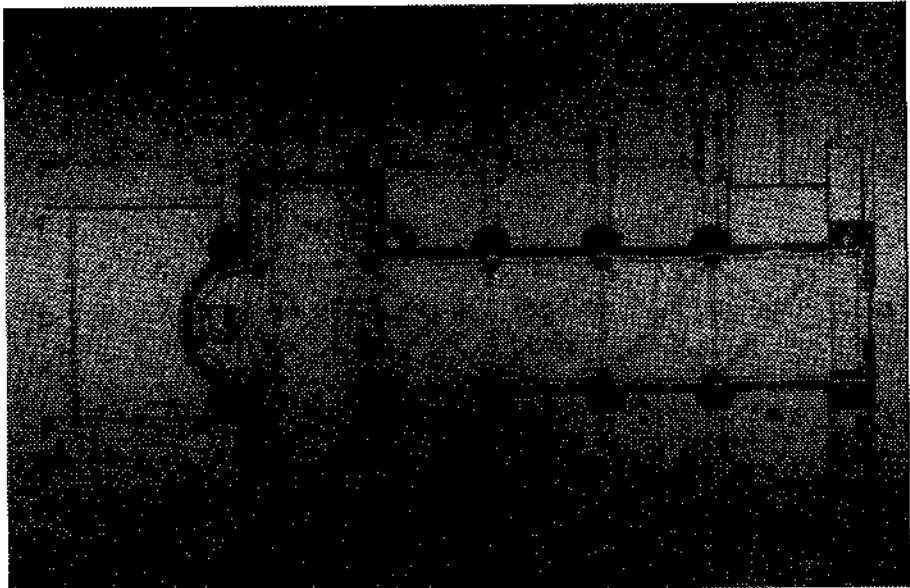


Figure 1: Plan of the Upper Church (from G. Rocchi)

The Upper Church (fig. 1) completely different, with high slender forms and full of light which filters through the legendary historic windows was probably concluded in 1253.

In the following decades most of the building structures of the Sacred Convent around the two churches was constructed, together with the papal palace, the cloisters, the cemetery areas, the dormitories and the other buildings necessary to a rather numerous religious community.

Great new impetus took place in the second half of the fifteenth century, above all under Pope Sixtus IV who with new buildings gave the architectonic whole its almost definitive order which was later completed in the seventeenth and eighteenth centuries with the finishing of the refectory, the dormitories, the staircases and the squares adjoining the entrances of the two churches.

In order to embellish the two churches with religious themes, the most important talents alive in that period were given the task of carrying out an uninterrupted series of frescoes in both the Lower and Upper Churches.

The leading artists working in Umbria as well as in the Florence or Rome areas were called upon, achieving an exceptional artistic production which constitutes one of the most cornerstones of Italian art between the end of the thirteenth century and the beginning of the fourteenth century.

The emergency sites

The earthquake of September 26th 1997 provoked a profound crisis throughout all the structural system of the Sacred Convent and the Upper Basilica with worrying imbalances and cracks.

At once the Superintendence for environmental, architectonic, artistic and historic treasures in Umbria, coordinated and supported by the Heritage and Cultural Activities Ministry with the collaboration of Professor Giorgio Croci and Professor Paolo Rocchi of the "La Sapienza" University of Rome, took action to set up with the utmost speed a series of emergency work sites in order to prevent further damage in the various

parts of the buildings which had been affected most seriously by continuous seismic activity.

More than ten work sites were organised through which the work necessitated by the emergency, financed by various governmental "Ordinances" which made it possible to oversee with prompt actions the damage provoked by the earthquake throughout the convent and the nearby areas.

The Basilica

Inside the Basilica the damage, although extremely serious for the consequences that it had caused, was mostly confined to a few specific elements: the vaults of the Upper Basilica (fig. 2), the tympanum of the left transept and the summit of the bell-tower.

The collapse of the vaults was due mostly to the enormous quantity of fill material accumulated throughout the centuries in correspondence with the imposts and reins of the vaults themselves (that is, in proximity of the external walls).

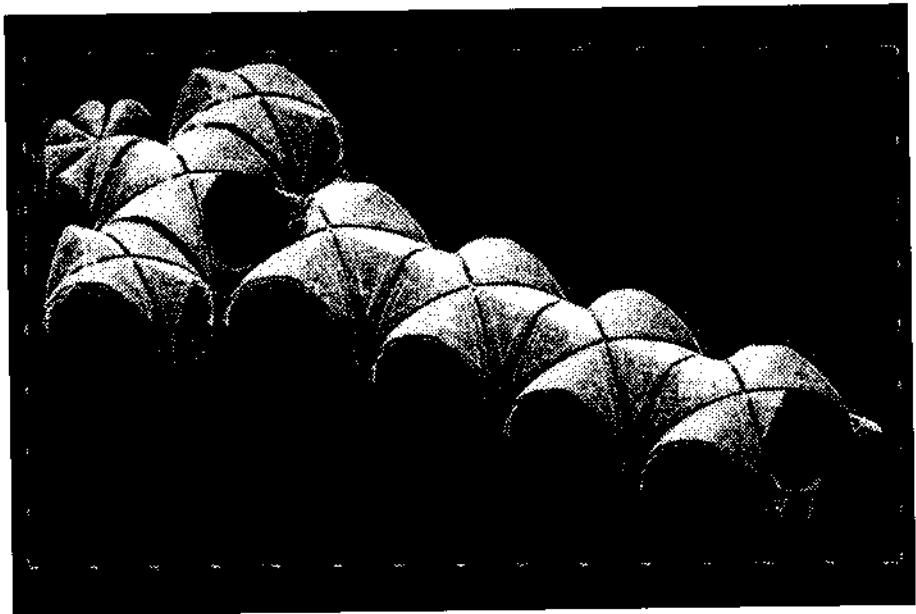


Figure 2: Assonometric reconstruction of the Upper Church vaults after the frame survey with the position of the gaps of the two segments of the fallen vault fields.

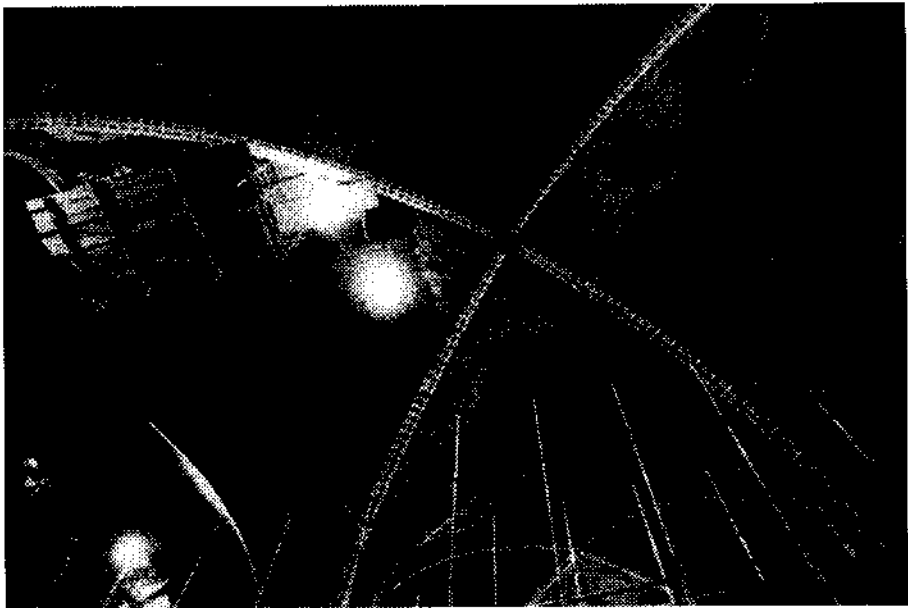


Figure 3: Portion of the fallen vault at the intersection of the transept with the nave.

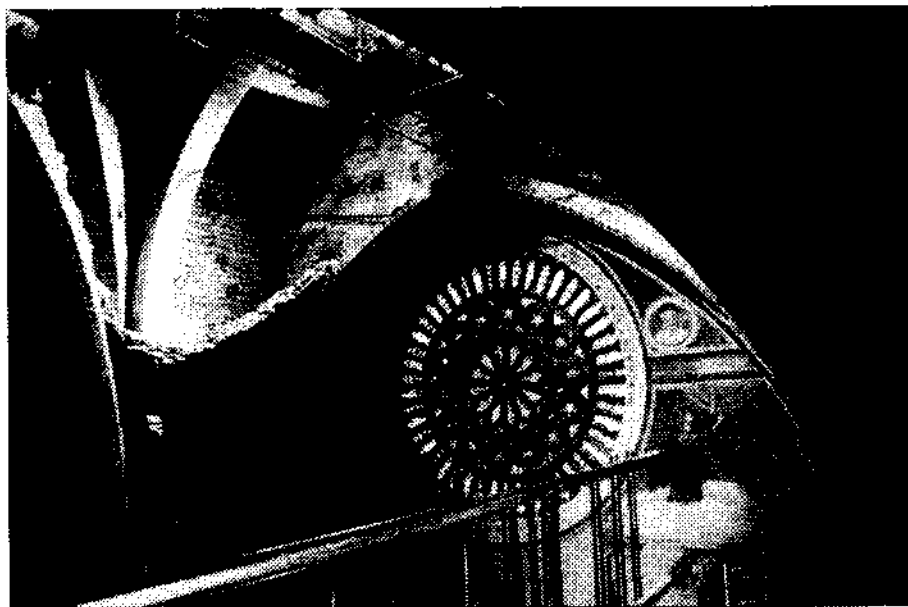


Figure 4: Portion of the fallen vault near the entrance.

This loose material, deprived of cohesion, produced under the effect of seismic action (with a horizontal component mainly perpendicular to the axis of the Basilica) very strong pressures, first on one side of the vault, then on the other, creating great bending and causing the loss of the curvature of the vaults themselves and of the ribbing which holds them in place.

Then the fact that the two vaults next to the transept (fig. 3) and to the facade (fig. 4) yielded is due to another phenomenon: these elements (the transept and the facade) represent the most rigid points in respect to the nave (which is more deformable) and it is precisely in this transition zone that the supplementary strains are produced which are then added to the previous ones.

However, all the vaults proved to be gravely damaged (figs. 5-6) with wide gaps and considerable permanent deformations which had altered the curvature and original form creating everywhere a situation close to collapse.

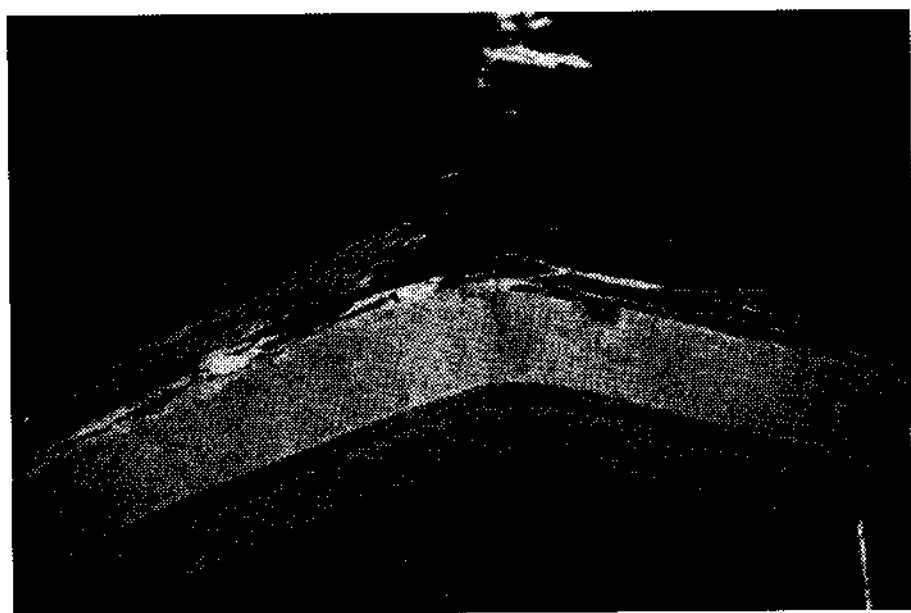


Figure 5: Series of damage on the vaults.



Figure 6: Damage on the vaults and on the rafters with the restorers at work.

The restorations carried out in the past and in particular the refacing of the pitch of the roof with a loft of bricks and tiles instead of the old wood loft had no connection with the damage suffered.

In addition, it should be remembered that the original wood roof had been replaced in the sixteenth century by great arches in masonry and only the pitches of the roof remained in wood. To avoid the danger of collapse, action was taken simultaneously on three lines:

- the removal of the enormous weight of the fill which amounted to about 1,000 tons for the whole Basilica;
- the compensation of the damaged parts with a salt free mortar so as not damage the frescoes; the strips opposite the damaged parts were thus soldered together, glueing them with strips of Kevlar and carbon fibres;
- the suspension of the more critical zones of the vaults to the great masonry arches which hold up the covering by means of a series of small tie-beams; these tie-beams contain two springs in order to provide a constant force,

independently of thermal effects or other deformations.

The consolidation of the vaults

The consolidation of the vaults (fig. 7) was a most delicate structural problem and necessitated the use of a mortar which had to satisfy a multiplicity of requirements:

- great fluidity since it had to penetrate the damaged parts and the tiniest cracks,
- the capacity to be dry-injected, that is, without first wetting the surface of the damaged parts;
- excellent adhesive and resistant qualities. In effect, it was necessary to have a far greater resistance than the minimum required, since even with all the action taken and checking adopted, it was still possible that the mortar would not succeed in spreading everywhere and therefore the resistance and linking between the two strips would be in the hands of one portion of the concrete section,
- compatibility with the frescoes.

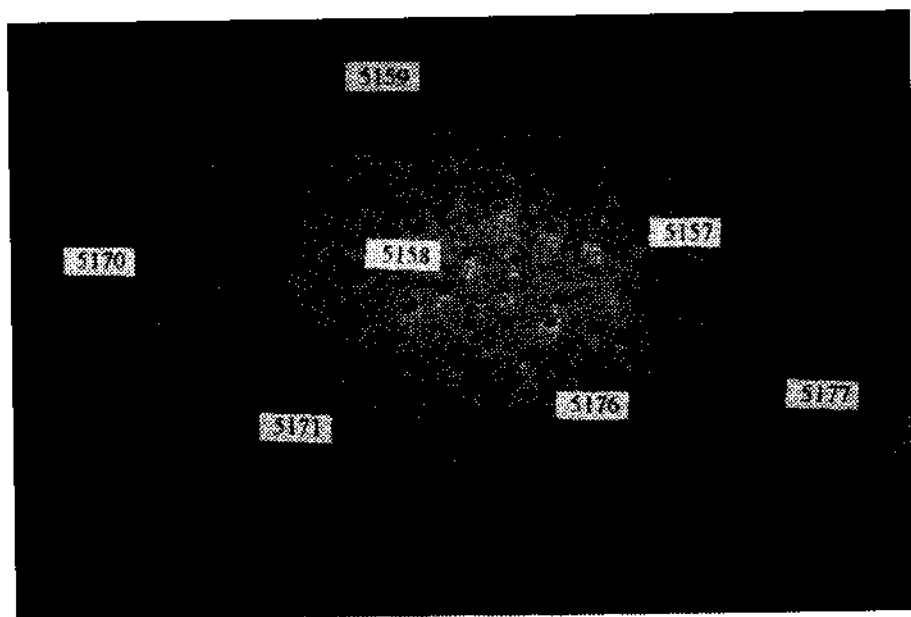


Figure 7: Portion of the vault showing the precise points in which the fluid mortar was injected for structural regeneration.

In order to choose the most suitable mortar, on the basis of precise instructions from the I.C.R. (Central Restoration Institute) as far as regards the composition of mortars tested on the last point mentioned injectability tests and the mechanical testing for breaking for bending and the cutting of small masonry elements reproducing similar situations and real ones on site were carried out.

The work of consolidation of the vaults was completed having previously made sure of the adhesion of the frescoes and compensated the damaged parts to the lower surface of the vaults.

The reconstruction of the vaults and the great transversal arches

The operation of the recovery and sorting of the debris enabled several portions of the broken arches, made up of bricks which in spite of falling from a great height had remained linked to each other, even keeping a large part of their frescoed surfaces, to be identified and retrieved.

Thus, in the reconstruction of the great arches it was possible to use all these elements and to recompose others so as to recover the authenticity of these even though they have been partially integrated with new bricks.

The consolidation of the recovered elements was carried out in laboratories under the care of I.C.R. experts making the stone elements of a width varying between 40 and 60cm; to improve adherence between the bricks some small Kevlar bars were inserted longitudinally.

Experimentation of the materials for reinforcing the vaults

The experiments on the composite materials were carried out between June and July 1998 and in the initial phase involved the experimenting of the single components and the perfecting of the composite material and in a second phase the testing of a nervure element and its collaboration with a wall element.

The results of the first phase enabled us to perfect a nervure

composed of a central nucleus of wood, to avoid every phenomenon of local instability through compression and cutting stress and an outer skin in fibrous material soaked in epoxy resin with reinforcement in one directional Kevlar on the lower surface and one directional glass fibre on the upper surface to withstand bending stress.

Anchoring the Renaissance arches

The Renaissance arches rest directly on the original modest support of the vaults (not to be confused with the enormous fill accumulated over the centuries above the vaults and which was the main cause of its collapse and imbalance) moreover, the great arches are not in alignment with the nervure below and are greatly eccentric to the supporting pillars.

The hooping (fig.8) and anchoring of the great arches to the walls in the bases of arches and to the towers provides a solution for construction imperfections directing the pressure to the vaults' support pilasters.

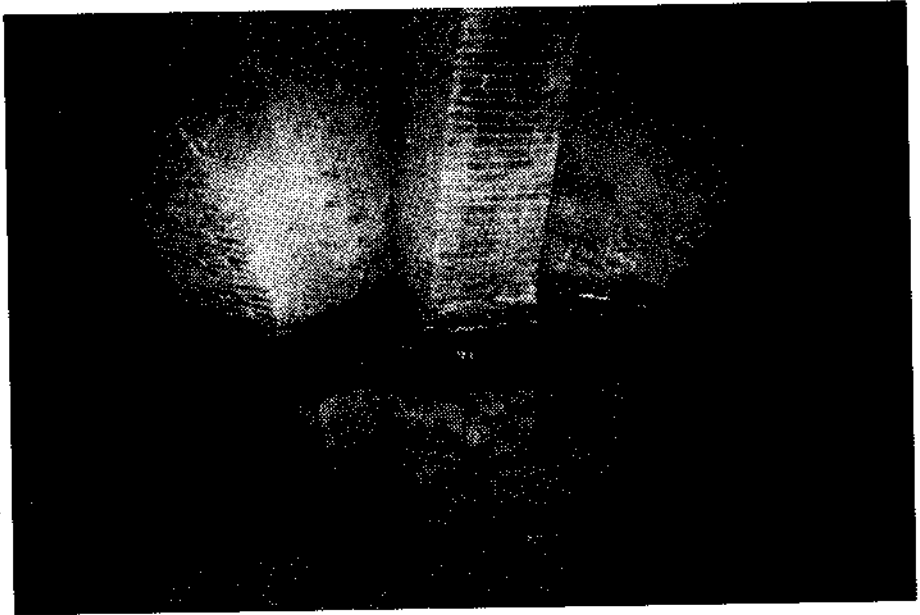


Figure 8: Circling with metallic elements at the base of the great Renaissance arches supporting the roof.

The transept Tympanums

In the tympanum of the left transept the provisional metal propping-up structure was removed and the seriously damaged upper part was dismantled.

The recovery of the stones and the installation of the new ones taken from a quarry with characteristics similar to those of the original ones were carried out.

The tympanum of the right transept which at first had seemed intact, had in fact also undergone severe deformations with a swelling which amounted to ten centimetres; by using a system of jacks this deformation was rectified and the consolidation and restoration work proceeded.

The Reconstruction of the Vaults

This operation posed diverse problems of a projectural and operational nature. First of all, the choice of materials. It was decided to use bricks of the same dimensions and form as the original bricks, the constituent elements of the transversal arches retained their trapezoid form alternating the way they lie with vertical elements and horizontal ones, avoiding interlacing between the arches and the dome segments, according to the original construction technique.

The manufacture of the bricks was carried out using traditional techniques in a small local kiln, using clay material of exactly the same composition as that of the original bricks.

As for the mortar, preference was given to using a pre-mixed component with a base of hydraulic lime, which had already given excellent results in the gap-filling phase, characterised by considerable adhesion, good mechanical characteristics and volumetric stability.

Another problem which required much analysis and thought was that relative to the form to be given to the two transversal arches which had to be re-built.

In fact in the absence of surveys prior to their collapse, and in the presence of significant impost deformations, it was decided to adopt a middle line of the projection of the residual arches.

As regards the arch above the altar, once the excessively deformed portions and micro cracks on the imposts – because of to the shaking due to the earthquake – the resulting curvature appeared correct from the static point of view and perfectly able to be joined to the impost structure.

However, the joining of the great arch near the facade with the right impost was much more difficult, where the deformation dates back a long time and is of far greater extent. In this case it was decided to maintain the “ideal” curvature by adapting the support to the deformed impost after, however, inserting some tie-beams to anchor the deformed impost to the body of the structure.

As far as the reconstruction of the barrel vaults (fig.9) was concerned, in order to have an efficacious support on the diagonal rafters (and as far as the facade on the captive arch is concerned) the remaining strips of the original dome parts were removed, after proceeding with the provisional detachment of the plaster. In this case too, the notable deformation of the impost elements made necessary the dismantling of some limited parts for the purpose of reaching sufficiently reliable support sections.



Figure 9: Arranging the filling material for the reconstruction of the vault segments.

In the rebuilding of the ribbed beams some elements obtained from the pre-assembly of bricks and blocks which had fallen and been retrieved were used, whereas in the reconstruction of the vaults account was taken of the deformation of the vaults themselves and the great transversal arch following the removal of the centring.

To compensate these deformations it was decided to use a system of jacks. The use of volumetrically stable mortar then reduced the amplification of the phenomena in the long term compensating for the viscous deformations.

In order to apply the jacks astride the keystone of the great transversal arch provisional steel plates were predisposed; as regards the barrel of the vaults above the altar, temporary joints along the arches and in the keystone subdividing effectively the vault into four segments were made.

The first phase of the setting in place concerned only the great transversal arch before finishing the dome segments to a weight value so as to produce a slight raising of the keystone; in this way the load applied successively with the construction of the dome was only partially transmitted to the centring, whereas it fell mostly on the great arch recomposing in this way a weighting process similar to the original one.

The dome segments were set in place longitudinally with jacks placed along the great arch's line of discontinuity in such a way as to create a contrast with the diagonal great arches; thus the joining was solidarized.

The same procedure was followed for the weighting pressure of the transversal section for which the great arch was involved once more.

The load applied to the jacks was decided on the basis of a structural analysis of the vaults; the loading phases were recorded using a monitoring system which availed itself of a series of strain-gauges applied on the transversal great arch and deformation gauges applied in the keystones.

At the conclusion of the reconstruction work, after the removal of the centring, less than a millimetre, an extremely small vertical deformation, was recorded.

The Restoration of the transept tympanums

In the left transept tympanum the interventions realized were in accordance with the projected forecasts already contained in the definitive project which are set out in line with the general methodological directions to which reference was made for every part of the building complex.

In more detail, the dismantling of the upper part of this element, damaged so seriously as not to allow consolidation, was completed; therefore, the reclamation of the part underneath proceeded compensating the damaged parts, filling the gaps and taking particular care in reconnecting the external facing with the packing in a reliable way; the reconstruction of the dismantled part was finished putting in place the utilised blocks of stone material recovered after the collapse, integrated for the origin and morphology and using for amalgamation of the stones, linking with a base of hydraulic lime.

In order to constitute a more reliable element with which to connect the tympanum, two "strut" elements were made on the heads of the roof pitch and a closing "straight brace" element horizontal, steel, to constitute a sort of truss on which to position the consolidated and restored tympanum.

The connection was entrusted to a system of metal plates and a layer of isolating material between the back tympanum and roof head as well as linking pivots equipped with energy dispersers.

In fact, in order to integrate the connection between the tympanum of the left transept and the back heads of the roof pitch, devices with form storage materials which reduce the impact in the event of seismic activity were installed.

For the right transept tympanum, in the end, the off line proved to be over 10cm, adding up the disconnection between the external facings and packing to the rotation of the rigid element. This deformation was almost completely recovered by means of the action of flat jack system. The technology of reconstruction and consolidation are similar to those used for the left transept tympanum.

After the phase of reconstructing the fallen vaults and the structural reclamation with systematic injecting of hydraulic mortar to make good all the discontinuities and existing cavities came the concluding phase of structural reinforcement of the vaults through the realization of the stiffening nervures and the system of spring suspension.

Reinforcing the Vaults

The consolidating intervention consisted of the construction of reinforcing and stiffening nervures (fig.10) on the back of the vaults both in correspondence with all the ribbing present on the lower surface and in the areas of the vault segments comprised between the ribbings themselves.

Moreover, in order to further limit the deformability of the vaults, the possibility of transferring part of their weight to the structure of the weight above by means of helicoid spring suspensions were provided.

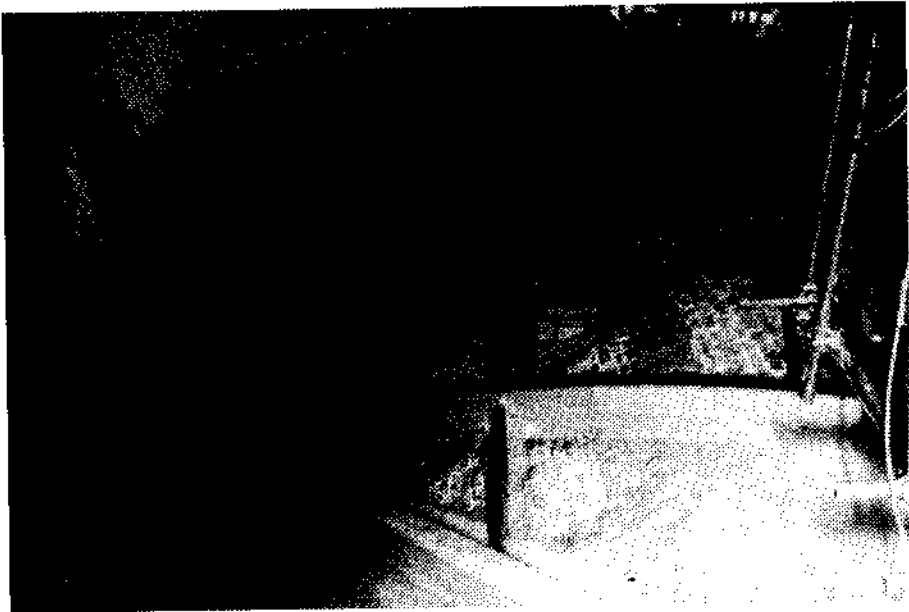


Figure 10: Reinforcing and structural improvement nervures carried out on one segment of the vault.

All the reinforcing nervures are in composite material and have a core in rectangle-sectioned, nautical mahogany plywood, covered in aramidic fibre material and epoxy resin. In addition to covering completely the wood core, the fibre was also extended to the extrados of the vault, forming a strip of between 20 and 30cms in length between the two sides of the nervures and extending through its entire length. On the upper facade of the nervures to the fibre covering were added pulltruse sections in aramidic fibres.

In correspondence with the great transversal arches two adjoining nervures were realised, with one section 22cm long and 10cm wide, equipped with transversal stiffenings which help in reducing the deformability to an acceptable portion of the roof vault. The only nervure provided in correspondence to the longitudinal arches adjoining the lateral walls is of the same section and type.

Also in correspondence to the diagonal ribbing one single nervure of the same type as the one described above but with one section 30cm high and 12cm wide was provided.

In addition one or two intermediate nervures were placed for every vault segment of section 18-20x5 cm which radially branch with respect to the pillars.

All the nervures are inter linked both in relation to the vault ridges, by means of 18x12cm section reinforcements as well as in relation to the imposts where the nervure edges reinforced by suitable steel supports are linked to each other and to the surrounding brickwork by a tubular stainless steel component. Into each vault segment a further connection carried out by means of a suitable nervure placed approximately halfway along the vertical development of the segment, parallel to the vault ridges in 12x5cm section and internally equipped with a stainless steel tube was introduced. The presence of tubular steel reinforcement made it possible to hook onto these intermediate nervures suitable helical suspension springs to the roof structure.

The connection between the reinforcements described and the masonry structure of the vaults came about partly through direct glueing by means of epoxy resins which go on in addition

to making up the matrix of the structure of the nervures themselves and in part through pivots in unidirectional aramidic fibre and epoxy resin fixed to the brickwork itself.

In relation to the vault fields the pivots were fixed ortoganally to the top end of a brick for the purpose of reducing the risk of the resin percolating through the joints as far as the surface of the lower masonry. In relation to the ribbings of the lower surface, however, it is necessary to ensure that they are firmly connected to the reinforcing structure. Besides, ribbings such as are not connected structurally to the vault fields on which they simply lie. Thus it was necessary to insert deep pivots, inclined and of larger sections than those provided for the vault fields.

The material chosen for reinforcing the extrados, the upper surface is aramidic fibre with a epoxy resin matrix since out of the materials currently available with the most advanced restoration tecnologies it is the most suitable to be flanked with a particularly important and delicate brickwork structure. In fact the aramidic fibre possesses an elasticity interior to that of steel of titanium and of carbon, reducing the problem of the creation of dangerous tension concentrations in the brickwork near the reinforcement, whereas at the same time it possesses high resistance to breaks, allowing the realization of structures with relatively reduced mass, an advantage not to be overlooked in restoration which must stand up to seismic action. The aramidic fibre also has the advantage of not being fragile (unlike carbon fibre), of standing up well to stress and of possessing good spread ability qualities.

Structural Improvements

In order to improve the resistance of the structural organism of the Basilica, a grid trussing was set in place on the inside of the Upper Basilica at floor level height, at about eight metres above ground level where Giotto and his pupils illustrated the life of St. Francis.

This system was conceived with the two-fold purpose of "uniting" the various zones of the Basilica and of also reducing the horizontal deformability of the perimetral walls subject to dynamic horizontal and orthogonal pressures on their vertical floor.

It is, indeed, necessary to consider that every field of the lateral walls of the nave and the upper parts of the transept are known to be particularly weak in their central zone. This is because of the presence of elongated double-lancet windows of the Upper Basilica and corresponding apertures (carried out in breccia) to allow access to the side chapels in the Lower Basilica.

Moreover, in the Upper Basilica the perimetral walls present damage often of a passing nature (produced by seismic activity in past times) in almost every field, centrally, from floor level as far as the above mentioned windows; this damage which therefore affects the frescoed areas which have been plastered over and re-painted time and time again.

In short, in the current situation the limiting walls appear to be connected in an efficacious way, from area to area only a foundation level on rock and from the flanks of the roof for which a further linking with an intermediate quota seemed opportune.

Furthermore, the insertion of steel beam provided a suitable reserve of flexibility to the various areas of wall brickwork which otherwise they would have lacked because of the presence of the lancet windows and the old damage underneath. The beams made with metal components were laid in the hollowing originating from the reduction of the brickwork thickness to a level of 7,8 m from the floor. A regular series of slabs linked to the brickwork apparatus underneath, whose morphologic and mechanical resistance characteristics had previously been verified, make up the support system avoiding any interference with its original support and its precious paintings.

The trussing, constructed in parts and assembled on site in the linking of modular components provide the interpositioning of suitable oleodynamic joints in a position to allow shifts in length variations induced by changes in temperature also guaranteeing a strong connection in the event of earthquakes.

The transversal profile of the beam is tapered towards the centre of the nave so as not to interfere with the aesthetic value of the surroundings and our appreciation and interpretation of the wall-paintings and their precious meanings.

Upper Basilica roofing stiffening and impermeabilization intervention

The structure of the nave of the Upper Basilica in the zone above the contrast points of the external rampant arches presented a transversal deformability not sufficiently contrasted by the high cylindrical counterforts which besides with their considerable weight made the effects of horizontal accelerations even worse. Such deformability is one of the causes of the fall of the vault fields at the extremity of the nave itself, that is, of the segments where the cutting stress due to the transversal component of seismic acceleration is at its maximum.

Since therefore it was necessary to ensure upwinding at the higher levels stiffening action of the roof pitch was carried out in their floor. It is essential to consider that the existing roof, realized at the end of the 'sixties with precompressed brickwork tie-beam simply flanked on, arranged according to the maximum gradient and covered with a layer of non-reinforced mortar of only 3cm. was not able to offer sufficient rigidity in the transversal direction of the axis of the Basilica.

Thus a grid upwinding was carried out placing flat elements (20cm. wide and 12cm. thick) in stainless steel along the top beam in reinforced concrete, along the longitudinal beams in reinforced concrete in correspondence to the side walls, linked transversally and diagonally with other flat elements in stainless steel (of the same dimensions) arranged in correspondence with the transversal and diagonal archi-tympanums.

The linkings between the various components took place by means of head-to-head soldering to achieve full penetration. Moreover, all the components were solidarized to the roof support system, that is, to the lateral walls, to the archi-tympanum, to the longitudinal beams and to the top roof curb-plate, by means of tshaped bars in stainless steel (Φ 18mm, 50cm thick) of an appropriate length.

The grid structure thus carried out is situated on the extrados of the precompressed masonry tie-beams of the present-day roof, after removing the layer of existing covering including the waterproof layer.

Once the grid structure was in place, this was recovered with an isolating warming layer in concrete with insert elements in expans-argil clay of an average thickness of 5cm, reinforced with metallic netting. Over the isolating a slate warming layer (fig.11) was put in place impermeabilized to the thickness of 4mm with fibre-glass material with average superimposition of 30% of the surface and soldering carried out while hot.

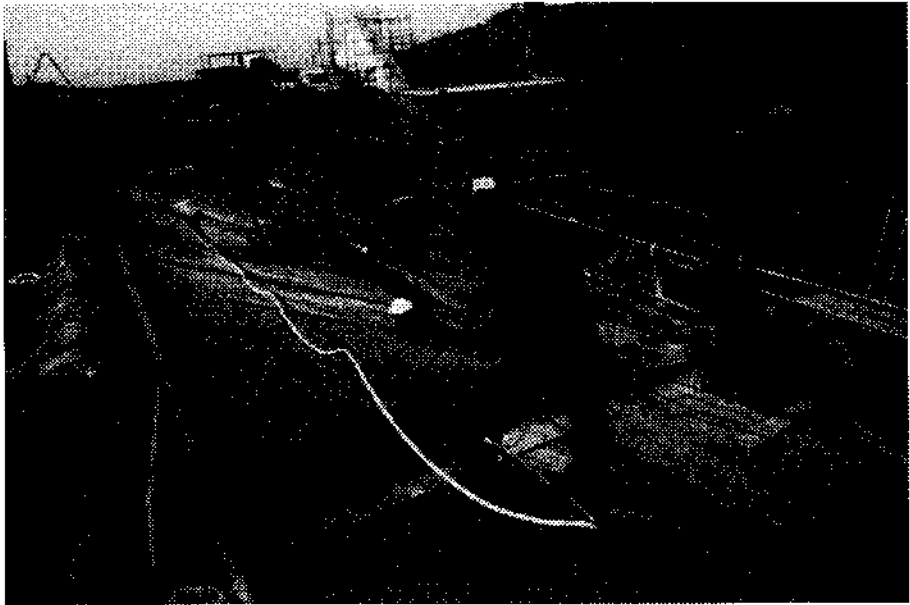


Figure 11: Positioning of the waterproofing girdle on the Basilica's roof pitch.

The surface of the whole covering of the church building complex carried out with this system involved an area of about 2,230 square metres. Once the operation had been completed, the covering layer was replaced using most of the original tiles (fig.12) and mixing them with new components of the same type as the existing ones.



Figure 12: Positioning of the tiles on the girdle.

At the present moment a monitoring system which will keep the more structurally delicate areas of the Basilica under surveillance is being studied.