THE COLLAPSES OCCURRED IN THE BASILICA OF ST FRANCIS OF ASSISI AND IN THE CATHEDRAL OF NOTO

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SUMMARY

The 13 March 1996 most part of the Cathedral of Noto, in Sicily collapsed and the 26 September 1997 two vaults and part of the transept of the Basilica of St Francis of Assisi collapsed too.
Both of them represent emblematic cases of the risk the monuments are exposed to, but they provide also a starting point to reflect how preventive measures should be taken to protect the architectural heritage.
This paper analyses the causes of these collapses and the measures that have been taken to prevent further damage and to restore the two churches.

I Introduction

This paper analyses the collapses that occurred in the Basilica of St Francis and the Cathedral of Noto to individuate their causes and describe the remedial measures that are going to be taken.
A portion of the left transept and two vaults of the Basilica of St Francis collapsed during the second quake that struck central Italy the 26 September 1997.
The earthquake in Assisi has been evaluated of the VIII degree of Mercalli scale; the acceleration measured at the ground close to the Basilica was 0,16 g in the direction of the longitudinal axis and 0,19 g in the perpendicular direction. Dynamic analysis and measures of the accelerations recorded in the following months (a system of seismographs was placed after the earthquake in the Basilica and the Convent) have shown that the amplification of the seismic actions between the vaults and the ground is about 3. This value may anyway be considered only as indicative because the quakes recorded after the stroke of 26 September did not reach values to get the structure behind the elastic levels, as happened at the time of the collapse.
The collapse of the Cathedral of Noto occurred unexpectedly the 13 March 1996.
The first element to subside, following the analysis and investigation that have been carried out, was a pillar close to the dome drowing down the dome itself and large part of the Basilica.
In the following paragraphs these collapses will be examined in detail and their causes will be discussed because both of them were in a certain way unexpected: the Basilica of St Francis in its history resisted to many earthquakes, some of them certainly higher than that occurred the 26 September 1997, and nothing special happened to the Cathedral of Noto the day, and the days before the collapse.
2. The Basilica of St Francis of Assisi

2.1 The Basilica of St Francis (Fig. 1), built in the 13th century, was hit by many earthquakes in its history. Earthquakes stronger than that of 26 September 1997 probably occurred in 1279, 1328, 1703, 1747, 1781, 1799, 1832, 1859, 1917, 1979, and yet no one produced damage as large as that: the destruction of the vaults close to the façade, of the vaults close to the transept, of a a portion of the left transept (Fig. 2) and production of large cracks and permanent deformation all over the vaults of the Basilica, letting them in a very precarious and dangerous situation.

FIG. 1 The Basilica of St Francis

FIG. 2 The collapsed zones in the Basilica
Besides the different impact that earthquakes of different characteristics may have produced on the Basilica, other factors have increased the vulnerability respect the past.

As regards the tympanum, made of a cavity wall with two faces and an inner fill, the cause of the partial collapse (the first damage was produced the 26 September, but it was the quake of 7 October to create a large hole in the wall - Fig. 3 ) was the decay of the mortar which linked the stones of the external face with the inner fill; the reduced cohesion and bond could not prevent single stone blocks to progressively detach each other and fell down.

As regards the vaults the collapse was produced by a large volume of fill, mainly broken tiles and other loose materials accumulated over centuries of roof repairs in the springer zones (Fig. 4). Under seismic actions 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 therefore increasing permanent deformations. When the quake of 26 September hit the Basilica it is very likely that permanent deformations, reducing the curvature and therefore the bearing capacity, were accumulated as consequence of the previous earthquakes.

FIG. 3 The damage in the tympanum of the transept

FIG. 4 The huge fill accumulated over the vaults
A general model (Fig. 5) and a global stress analysis of the Basilica has been carried out (Fig. 6); in particular a non linear model of the vaults has confirmed the decisive role of the fill (Fig. 7); when the horizontal acceleration reaches about 0,2 g, relevant tensile stresses are produced. The failure mechanism of the vaults close to the facade, 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 drawings the vault down with it (Fig. 8). A similar mechanism occurred in the zone close to the transept, where the second vault collapsed.
FIG. 7 Stresses and deformations in the vaults

FIG. 8 A photo taken during the collapse of a vault
The collapses were concentrated on these specific zones because, being the direction of the seismic action mainly perpendicular to the nave axis, it behaved globally like a "beam", where a kind of restraint at the ends was provided by the stiffness of the façade and the transept (Fig. 9). The results was that high normal and shear stresses where produced there, in addition to the "local stresses" resulting from the weight of the fill.

2.2 Urgent measures were required immediately after the earthquake to prevent the global collapse of the tymanum and of the vaults. The survived vaults were all affected by large cracks distributed both on the intrados and the extrados (Fig. 10); curvature, as already said, was lost in several zones (Fig. 11).

The danger that the standing vaults might collapse, and the consequent risk to the human life, precluded the possibility of supporting the vaults from the ground level. Instead, a platform was suspended from the roof above the vaults with the double function of inspection and of providing a base for working over the vaults (Fig. 12).
The urgent measures taken in the first month after the main earthquake can be synthesized as follows:

- removing the huge load represented by the fill in the springer zones of the vaults,
- filling 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,
- applying bands of synthetic fibres (kevlar) over the cracks of the extrados (Figures 13, 14)
- 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 (Fig. 15)

The cracked ribs were suspended from the roof as well with a system similar to the previous one after having placed underneath a kind of steel cradle filled with soft rubber in order not to damage the frescoes (Fig. 16).
FIG. 15 The system of wires and springs to suspend the vaults to the roof

FIG. 16 Suspension of the deformed fibre kerbs to the roof
As regard the tympanum the risk was that if it had collapsed it would have destroyed the roof of the chapel below, causing the loss of frescoes and works of art of inestimable value. After long reflections 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 resolved by using two cranes; a first one outside the Basilica complex lifted the second one 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 steel frame structure in the shape of the tympanum, a triangle 8 m high and 17 m at the base.

In the period of time between the 10th and the 14th of October all the operations were completed: 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 (Fig. 17); 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 on lifting the steel tympanum over the brackets (Figures 18, 19).

The following day the empty spaces and big holes were filled with polyurethane foam to provisionally stabilize the masonry (Fig. 20).

FIG. 17 A crane in front of the convent lifts a second crane over the wall into the courtyard
FIG. 18 The lift of the steel reticulated structure to provisionally stabilize the tympanum

FIG. 19 The delicate moment when the provisional structure is connected to the tympanum

FIG. 20 The poliuretane foam to fill the empty spaces between the stones of the tympanum
2.3 The problem of the definitive restoration and consolidation of the Basilica, especially as regards the vaults, has immediately appeared to be very delicate, because, due to the presence of the frescoes, it was impossible to recover the deformations and to re-establish, therefore, an adequate curvature and autonomous bearing capacity.

Different studies, researches and mathematical models have been carried out to decide which solution would have been the most appropriate to strengthen the vaults and secure their stability over the time, without risking to damage the frescoes and without compromising the historical value of the original vaults structure. Finally the choice has been to realize on the extrados a series of little ribs, following a pattern typical of Gothic structures (Fig. 21), letting clearly visible the original structure.

These ribs are made up of a composite material with aramidic fibers (Kevlar) bedded in epoxy resins and a central timber nucleus; this material is light, very strong (the tensile strength of the Kevlar fiber is 30.000 Kg/cm² and that of the fiber with resins is about 14.000 Kg/cm²) and less stiff of the steel (the elasticity modulus is respectively 1.200.000 Kg/cm² and 600.000 Kg/cm²).

Aramidic fibers, besides, haven’t brittle behaviours and present a good ductility.

The ribs are built in situ, so that it is possible to follow the deformed shape of the vaults: whilst the width of the ribs remains constant (8 cm), the height has an average value of 20 cm, but it increases or is reduced in relation with the deformation of the vaults, because the extrados of the ribs follows a regular curve parallel to the original ideal surface of the undeformed vaults.

FIG. 21 The plan of the new kevlar fibre kerbs to be realized over the extrados of the vaults
Different samples of the basic materials and of the composite ribs have been tested in specialized laboratories, as up-to-date there was not large experience on the application of these products to restore historic masonry structures; the results have been quite positive showing excellent resistance and good bond between the ribs and the masonry.

The net of ribs in a certain number of points will be sustained by tie bars connected to the roof; similarly to what was realized in the urgent intervention phase, a spring will be inserted in each bar in order to avoid excessive concentrated forces and to eliminate the influences of the temperature effects and of different movements between the roof and the vaults.

As regards the cracks, which have compromised the continuity of the vaults, it has been decided to complete the first injections realized in the emergency situation using a mortar able to satisfy very specific and severe conditions. It has to be salt-free and compatible with the frescoes, sufficiently fluid to penetrate and diffuse in all the cracks and microcracks; to be injected in dry masonry (no use of water is allowed); to have good strength and bond capacity to re-establish a structural continuity through the cracks. Accurate analysis and laboratory tests have allowed to individuate a special mortar, prepared by MAPEI, as the best to fulfill these requirements.

The operation of injection is carried out both from the extrados and the intrados of the vaults after preliminary having checked and well fixed the frescoes detached from the vaults (Fig. 22).

A further intervention regards the masonry arches which sustain the roof; their base actually simply stands on little arches which insist over the springers of the vaults without any structural connection and with a certain eccentricity respect the ribs of the vaults and the pillars.

It has been therefore decided to anchor the base of the arches at the walls and the towers behind, which in this very peculiar Italian Gothic have the function of abutments. The anchorage is realized with a steel belt and prestressed horizontal bars (Fig. 23).
The reconstruction of the collapsed vault 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 regard the pieces of ribs, although having felt down from 25 metres, had maintained a good bend between the bricks.

It has therefore been possible to assemble in laboratory the broken parts of ribs in such a way to create a sort of voussoirs about 40 - 60 cm long (Fig. 24); these voussoirs are then placed on a provisional centring to rebuild the ribs (Fig. 25).

It hasn’t been possible instead to recover significant elements of the webs, so that new bricks, expressly built to have the same constituents and similar characteristics of the original ones, are going to be used.

The reconstruction of the vaults has taken 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; a system of jacks has been foreseen for this purpose, placed in a provisional joint on the crown of the new vaults, to compensate the deformation, including the shrinkage of the mortar, and to calibrate the stress distribution.

The restoration of the Basilica is completed with the reconstruction of the collapsed portion of the left tympanum and the recover of the deformations that both tympanum have suffered; stones coming from the same original quarry are going to be used. To reduce the seismic actions transmitted to the tympanum, which even if consolidated remains a delicate structure, the connection between it and the roof will be realized interposing a specific device using a “shape memory alloy” able to dissipate a certain amount of energy.
3 The Cathedral of Noto

3.1 The Cathedral of Noto, built in the middle of the 18\textsuperscript{th} century, suffered during its life severe damage, partial collapses (the dome collapsed during the construction in the 1760 and, after having been rebuilt, again in the 1848, due to earthquakes), reconstructions and reinforcements, till the catastrophe of March 1996 (Figures 26 and 27).

Different factors have played a role in its vulnerability: the effect of frequent earthquakes, the huge weight of the structure and of the fill over the vaults (Fig. 28), the pour quality of the masonry realized with faces of stone blocks and a core of rubble without cohesion (Fig. 29), etc..

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{cathedral-of-noto-after-collapse.jpg}
\caption{The Cathedral of Noto after the collapse}
\end{figure}
FIG. 28 The huge fill and weight over the vaults

FIG. 29 The structure of the pillars; it is clearly visible the poor quality of the core
The survey of the debry (Fig. 30) and the structural analysis of the Cathedral (Fig. 31) have individuated that the collapse started by the crushing of the second pillar close to the dome on the right of the nave. Actually the stresses in the pillars were very high (20-25 Kg/cm²) and increased of around 20% during the earthquakes. The safety margin results therefore extremely low when compared with an average strength of about 40 Kg/cm².

In this sort of pillars (Fig. 32) most part of the load is sustained by the faces, whilst the core not only does not offer any valid contribution to the global strength, but, thrusting on the faces, creates on them supplementary bending stresses.

In addition, the blocks of the facing walls, to facilitate the construction, were not cut with parallel horizontal faces, but these are inclined inward so that only the external surface appears to be regular; as consequence the transmission of the vertical stresses is concentrated in areas, much smaller than the theoretical section, so that the stresses are substantially increased.

FIG. 30 The debry of the collapsed Cathedral
FIG. 31 A mathematical model of the Cathedral of Noto

FIG. 32 A detail of the structure of the pillars
Such unfavourable structural situation got worse when little vertical cracks were produced by the earthquakes and the rainwater penetrated inside, not only increasing the load but also accelerating the decay of the pour mortar.

Signs of danger were surveyed on some pillars four years before the collapse, so that in February 1992 a provisional strengthening, shoring the pillars themselves with a system of horizontal steel tubes, acting as stirrups, was realized. This measure, however, was not sufficient to stop the evolution of the crushing phenomenon: when the stresses are close to the strength, actually, crushing goes on “spontaneously” with progressive extension of vertical cracks and outward deformations; the facing stone blocks are then not able to provide a “circumferential resistance” anymore - nor could the weak provisional steel tubes - counteract the lateral pressure of the rubble core: the pillar then suddenly “explodes” (Fig. 33).

The second pillar from the dome on the left of the nave, whose section is reduced regard the four pillars under the dome, was the one to reach higher stresses, being also weakened by a passage to go up to the pulpit (Fig. 34).
The collapse of a pillar has always catastrophic consequences and in this case the consequences have been even worse of what it could have been expected, probably because the original timber roof was replaced with a reinforce concrete slab, in the middle of the 20th century (Fig. 35). This continous slab has spread the overloads produced by the collapse of the second pillar progressively on all the other pillars, till the façade of the Cathedral.

Fig. 36 shows the dynamic of the collapse as it has been possible to detect by the survey and analysis of the debrý.

FIG. 35 The continuous reinforced concrete slab that in the middle of the 20th century replaced the original timber roof

FIG. 36 The dynamic of the collapse
3.2 The first urgent measures, taken to prevent further collapses, consisted on realizing on the one hand a strong steel structure to support the survived portion of the dome (Fig. 33) and on the other transversal stirrups to reinforce the survived pillars, as their weakness remains as an intrinsic aspect related to the original materials.

The final consolidation and restoration of the Cathedral of Noto does not pose structural problems as difficult as those faced in the Basilica of St Francis, because on the one hand there are not such valuable frescoes and pieces of art, and on the other, as most part of the Cathedral collapsed, it has to be rebuilt, what is much easier than to repair and consolidate.

Techniques and materials similar to the original ones will be used, eliminating anyway what can be referred to an imperfect original structural realization: as the pour quality of the mortars, the loose rubble (which formed "the core" of the pillars), etc.

Particular attention will be played to the connection of the survived portion of the collapsed dome with the new structure in order to minimize the discontinuity in the strain and stress distribution.

Finally it will be necessary to strengthen the survived structures and mainly the pillars, where the loose rubble core has to be consolidated with appropriate grouting and a system of horizontal stirrups.

FIG. 37 The provisional shoring of the dome
4 Conclusions

The collapses and damage which involved the basilica of St Francis of Assisi and the Cathedral of Noto have very different origin and very different has been the mechanism of collapse.

There are, however, common aspects in the two cases: the inappropriate human action (the fill accumulated over the vaults in the Basilica of Assisi, the passage realized through the weakest pillar in the Cathedral of Noto and the insufficient provisional measures taken four years before its collapse) and the lack of systematic structural survey. The last point poses once more the big question of a “prevention of risks” policy, including ordinary and extraordinary maintenance, and the need of plans of survey and investigation in good time to detect structural imperfections.

A close investigation would have allowed to discover that the vaults of the Basilica of St Francis of Assisi had suffered progressive deformations, reduction of the curvature and increased cracks in occasion of each of the main earthquakes occurred in the past, and that their bearing capacity was progressively reduced. As regard the Cathedral of Noto a skillfull survey would have shown that the little vertical cracks appeared in some pillars were not just superficial signs but a serious indication of an incipient crushing phenomenon.

More difficult would had been to detect the intrinsic weakness of the masonry of the tympanum of the basilica of St Francis and of the pillars of the Cathedral of Noto: some specific tests and endoscopic analysis could have anyway given useful information.

In conclusion, structural risks will never be totally eliminated in historic buildings; these risks, however, can certainly be reduced if the “risk prevention” culture - and in particular systematic maintenance and survey - prevails, instead of repairing and strengthening only when severe decay, damage or collapses have occurred.