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GELATI MONASTERY ADVISORY MISSION REPORT

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EXECUTIVE SUMMARY

The engineering-geological survey showed that the territory of the monastery and the adjacent area are in a satisfactory condition. The research area consists of the consolidated gravel, clay and dolomitized limestone layers. All the buildings of the monastery are based on the limestone rock. The foundations of the Holy Mother Birth main church are built of processed dolomitized limestone in lime mortar. The analysis of the existing conditions, carried out by Georgian experts, proves that the overall strength of the foundations’ masonry makes it impossible for unexpected deformations to occur. The characteristics of the soil do not seem to have an influence on the settlements of the foundation of the church, and, accordingly, to the dome. It is more likely that the effects on the dome are due to seismic action, and in that case some specific research on the characteristics of this action (magnitude, intensity, epicentrum and frequency) should be done in the development of the project.

The stone elements of the building have been significantly damaged for various reasons: due to earthquakes as well as man-made interventions. However the most significant impact on the building has been caused by rain and wind. The cornice stones are damaged almost to the same degree all over the church and do not fulfill their protective function anymore. Despite the abovementioned damage, the overall bearing structure of the church — foundation (stereobate), crepidoma, walls and arches — is mostly in satisfactory condition and does not seem to require heavy structural interventions. In fact the geometrical shape and the walls, interconnected each other, have a kind of abutment effect. The result is a rigid body able to counteract the thrust of arches and vaults and the forces produced by the earthquakes.

This general aspect, however, doesn’t guarantee that the structure doesn’t present risks, considering the incertitude that we have today: the real efficiency of the connections between the walls and the other structural elements are not known; the effect of the deep decay which may reduce the strength of the stones and probably reduce the efficiency of the structural cooperation between the different elements is also unknown.

The construction of scaffolding in the interior of the church up to the dome, gave the conservators the possibility to inspect the condition of the cracks on the cupola again. The result of these inspections is that the cracks are in evolution. At the moment it is impossible to take any major decision without knowing about the dynamics of the evolution, the distribution and the quantity of the opening of the cracks. Only after the analysis of this data, would it be possible to decide on the strategy which should be undertaken and particularly whether further strengthening is required.

Regarding the static and dynamic implications as well as the construction techniques of the beam recently built at the top of the drum of the main church of the complex, made of lime mortar reinforced with steel bars and anchored with steel bars to the existing stone structure: To eliminate the risks, often an annular chain (made of steel, wood, concrete etc.) or a small ring-beam is placed in this zone. The ring-beam already produced represents one of the possible reinforcements and, on this aspect, it is correct and justified. The ring-beam appears compatible with the historic fabric of the building and, being constructed in lime mortar and reinforced with stainless steel, is able to provide the
required resistance. From a structural point of view, the ring appears to be efficient. The tension stresses are absorbed by the resistance of the reinforced ring. This circumstance gives an important role to the structural behavior.

According to the solution that was suggested and executed by the Georgian experts, vertical bars incorporated into the body of the ring were installed simultaneously by core drilling into the body of the cornice stones, connecting both systems and increasing the stiffness of the cornice. This way, in case of future seismic stresses, possible horizontal movements of the cornice stones would be prevented. If necessary, the effect of the ring-beam can be improved by inserting, between the ring-beam and the base of the dome, a system of jacks able to produce supplementary horizontal, radial inward forces, pre-stressing the dome this way. Concerning the open joints and cracks on the stone window lintels, the mission does not think that further reinforcements to the upper part of the dome should be necessary. What is necessary instead is the local repair and consolidation of the stones, including injections and filling of the cracks.

The large windows of the drum produce a weak structure that may have problems under the effect of earthquakes, while the base of the drum seems to be the potential critical section. The situation here is still unknown, as nothing has been uncovered yet. Structural calculations are therefore necessary in order to analyze the behavior of the dome-drum system and consequently design hypothetic reinforcements.

The restoration work taking place at the level of the stone cornice of the drum is careful and systematic.

The key recommendations of the mission are highlighted in the final part of this report (on page 16)

DESCRIPTION OF THE EXISTING CONDITION OF THE BUILDING

1. Brief history of Gelati Monastery

The Gelati monastery complex is located on the left side of the river Tskhatsitela, 11 kilometers far away and to the North-East from Kutaisi city, on the plained side of a high mountain. The Gelati monastery is surrounded by a wall, and includes three churches: Holy Mother Birth main church (1106), Church of St. George (XIII century) and Church of St. Nikoloz (XIII century) (fig.1, 2). Located in the western part of the courtyard, there are the bell tower (XIII century) and Academy buildings (XII century) (fig.3). The Monastery includes several houses from the beginning of XVIII-XX centuries. The monastery wall has two gates, of which the gate located to the South is the most ancient one. Here the gravestone of David the Builder is located, and on a large architrave, there is the cast iron and steel door, the booty brought by Demetre I (1125-1155) from the Ganja fortress (fig.4). The east gate of the monastery that functions as the main entrance at present was built in the XVII century.

The Gelati monastery complex is amongst the monumental ensembles which preserves to a great extent the authentic appearance of the buildings to the present day, with the exception of the roofing.

2. Holy Mother Birth main church (Katholikon) (fig.5)

The central building of the Gelati monastery complex is the Holy Mother Birth main church. It is located in the middle of the courtyard. The building, in its content and composition, is
the dominant architectural complex. The main church (*katholikon*) of the ensemble is the first building that had become the starting point for the development of the large royal court monastery. Its foundation was laid by King David the Builder. All other buildings are located around the Holy Mother Birth main church.

3. Description and existing condition of the building construction

The building was composed in several construction phases. Compositionally, its structure was modified gradually, though the “new” buildings, attached later onto the main church body, have created and are perceived as one great church.

The plan of the building (fig.6), including the narthex, composes a rectangle, the south-west angle of which is cut off; the eastern side is finished with three apses stretched forward, while two other apses are located on the northern and southern arms. From the East, the cathedral is perceived as a five nave building, but inside the *naos* incorporates the three central apses and composes the cruciform type. The overall dimensions of the plan are 34,15 x 35,95 m. On the perimeter of the cathedral, the faces of the arches are elaborated with simple profiles and form joint curved surfaces, underlining their representation as carrying elements. The interior of the cathedral is completely covered with frescoes (fig.7, fig.8), while the hemisphere of the bema apse is partially covered by mosaic masterpieces (fig.9) - all carrying the results of old damages.

The engineering-geological survey showed that the territory of the monastery and the adjacent area are in a satisfactory condition. The research area consists of the consolidated gravel, clay and dolomitized limestone layers. All the buildings of the monastery are based on the limestone rock.

The foundations of the church are built of processed dolomitized limestone in lime mortar. The depth of the foundations varies from 40 to 150 cm. The analysis of the existing condition of the limestone and the lime mortar, carried out by Georgian experts, proves that the overall strength of the foundations’ masonry makes it impossible for unexpected deformations to occur.

The *crepidoma* (the visible top of the foundation) is built of basalt blocks (fig.10). It consists of three steps to the west and lowers to one step to the east. The bearing elements on the top of the *crepidoma* – walls and columns - are built of the same material. Their width varies from 81 to 150 cm. The cathedral is built of massive stone blocks, the dimensions of some reaching up to 4,50 x 1,70 m. The masonry is three-layered: inner and outer facing layers are connected with the in-between lime-concrete layer. While the building is decorated with a yellowish-color limestone, visually one has the impression that the limestone elements are cut from a different quarry, and so, they appeared to be of different solidity. The building is built firmly and each detail is carefully elaborated. In many places the sills are cut from a single massive stone, while the twofold arches over a large opening are also often used.

The stone has been significantly damaged for various reasons: mechanical, seismic actions, atmospheric downfall, seasonal temperature alterations and biological factors (lichens). The eaves stones are in the poorest condition (fig.11).

It is known that throughout history the building has been affected by earthquakes as well as man-made interventions. These traces are clearly visible on the body of the church and are marked on the measured drawings (fig.12). The connections of the secondary volumes with the main structure of the church have been weakened and the weathering of the facing masonry is evident (fig.13). However the most significant impact on the building has been caused by rain and wind (fig.14).
The abovementioned-damages are not as important as those of the cornices, where the degree of deterioration caused by weathering is immense. The cornice stones are damaged almost to the same degree all over the church and do not fulfill their protective function anymore (fig.15, fig.16, fig.17).

Despite the abovementioned-damage, the overall bearing structure of the church – foundation (stereobate), crepidoma, walls, arches – are mostly in satisfactory condition and do not seem to require heavy structural interventions.

4. Description of the cupola supporting system

The cupola (with inner diameter 9,66 m) is lit by 16 elongated arched windows (fig.18). The thickness of the drum walls in-between the windows is 0,85 m. On the exterior side the width of the openings is 0,55 m. and of the walls in-between is 1,68 m. The total height of the building to the top of the cupola is 35,26 m.

The cupola of the church is mounted on the arms of the central (triumphal) apse and on the west pair of pillars. At these points, the moderately extended northern and southern arms meet together. The western arm is traditionally more developed. These four arms compose the volume of the central hall (naos). The roofs of the adjacent rooms cascade down on the four sides from the cupola. The main bearing structure is concentrated around the cupola, by the four main arches.

Actually, the dome rests not on four separate columns, but on a pillar system, reinforced by transverse and longitudinal walls: precisely those forming to the eastern part the enclosed two-storey parabemata (Prothesis and Diakonikon), while to the western part - the unique two-storey lateral compartments; these constructions, in addition to their functional utility, enhance to the maximum extent the support and stiffness of the drum-dome system (fig.19, fig.20, fig.21). The longitudinal and transversal stability of the main arches is secured by the additions which represent the outer naves. The main and auxiliary supports compose the bearing system holding the dome and the drum and, together with the perimeter walls, ensure the overall stability of the building.

REVIEW OF THE EXISTING DOCUMENTATION OF THE WORKS ALREADY CONDUCTED IN GELATI MONASTERY MAIN CHURCH (HOLY MOTHER BIRTH CHURCH)

Studies already conducted:
- Geological Studies
- Archeological Studies
- Art Historical Studies
- Engineering Studies
- Architectural Survey
- Mural paintings
- Stone conservation

1) Geological studies

Geological studies have been conducted in two phases: 1st in 2004 and 2nd in 2008. During the first stage, 7 pits were opened and during the second, 31 pits. The studies showed that the main church has a strip foundation, built in rough stone on the lime mortar and it lays on the dolomitized limestone at a depth of approx. 1,50 m. Both the stone and lime mortar strength characteristics are satisfactory.
2) Archaeological studies

Archaeological studies were conducted in 2007-2010, when 14 pits were opened. During the study it was revealed that the original roofing was made of glazed ceramic tiles. Due to this result, the configuration of the roofing and the color of the tiles were elaborated. The discovering of the old drainage around the church foundations has also been discovered, which contributed to the understanding of the system of rainwater removal. Further elaboration of the Master Plan of the site has also been based on the archaeological study results.

3) Art Historical studies

The study was dedicated to the research of the roofing of the main church in Gelati Monastery. It investigated the historical sources and archeological material due to which different layers of the roofing have been determined:

- 12th-14th c. with dark green glazed ceramic tiles;
- 13th c. stone slabs, which covered St. Marine chapel;
- 16th c. light blue glazed ceramic tiles;
- copper roofing (mentioned in the literary sources of 1650-1652);
- wooden roofing (mentioned in the literary sources of 1772);
- tin roofing (mentioned in the literary sources of 1772).

4) Architectural survey

Detailed architectural measurements were conducted by a German expert team, based on contemporary survey methods. Within the framework of the survey project, information is included related to the kind of damage of each stone of the masonry face of the main church and its location height. This documentation vividly shows that a significant number of stones are damaged by atmospheric downfall (Fig.12).

5) Engineering study (Appendix – Engineering Presentation)

The engineering-technical study envisaged the opening, probing and visual examination of the roofing. It revealed that a significant crack was present on the south-east part of the dome, which reaches the arches of the drum window openings. This particular crack had been documented and filled-in by lime mortar in the 1990s.

Main problems revealed:
1. The scaffolding in the interior enabled the project team to investigate the crack. The close examination revealed that the crack is in dynamic condition while additional cracks had been investigated during the filling process.
2. The cornice stones are cracked, which is mainly caused by the direct contact with wooden rafters, during wind.

The visual inspection of the dome roofing revealed the presence of the well-preserved oak beams from 19th century.

1. Historical evidence on the dome cracks

Georgian scholars suppose that the hemispherical dome of the church was originally covered by rough "filling" of stones in mortar, forming thus the traditional Georgian conic-formed dome. This "filling" apparently exercised sufficient load onto the cupola. The conical dome was covered by tiles, traditionally placed in lime mortar. In situ archaeological research proved that the tiles were colored and glazed. This technique was used previously in other Georgian medieval churches, like those of South Georgia, as well as the churches of Ishkhani (10th - 11th c.) (fig.22) and Khakhuli (second half of the 10th c.) (fig.23), still preserved on the territory of modern Turkey.
In the 18th century, during a repair of the roof, all the surplus “filling” was removed and the hemispherical dome remained “naked”. On the outer surface (extrados) of the dome a new wooden frame in oak beams was built, which gave the conical shape of the dome (fig.24, fig.25), covered perhaps with new tiles. The roof was stretched 30-40cm from the cornices, aiming for the rain water to be directed as far away from the facing walls, as possible.

In the 1940s restoration was carried out on the mosaics on the church apse. There was no reference of any particular crack on the cupola frescoes during this intervention.

During restoration in the 1950s, by architect-restorer V. Tsintsadze, the church was covered by tin plates onto the old oak rafter covering. No evidence for any crack on the cupola extrados was mentioned.

In 1960 the tin covering of the church roofing was replaced, but even then there was no documentation on any crack on the extrados of the cupola, neither was there any inspection of the interior cupola frescoes.

In 1990 there was an inspection of the existing condition of the interior frescoes. It was only during this survey and inspection that the existence of a crack pattern - that had not been reported before - was observed, though it was not possible for the eventual presence of any cracks on the extrados of the dome to be investigated, due to the difficulty to enter the empty space between the cupola and the wooden roof construction. However, the conservators decided to fill-in the crack with mortar for conservation reasons with regard to the frescoes, without any benefit to the stability of the construction of the dome.

In 2007, during fresco restoration works in the interior of the church, cracks were diagnosed on the row of cornices and were injected with an alabaster mixed solution.

2. Existing condition of the cupola

Starting in November 2013, the construction of the scaffolding in the interior of the church up to the dome, gave the conservators the possibility to again inspect the condition of the cracks (fig.26, fig.27, fig.28). It was discovered that the main crack had been widened along the cupola meridian (fig.29), and even continuing on the arches of the drum windows (fig.30, fig.31, fig.32). Similarly, the injected cracks on the frescoes had (re)opened. Unfortunately at that time there was no possibility to make detailed crack pattern documentation.

In parallel, the opening of the wooden roof was decided (fig.33, fig.34, 35), and after the cleaning of the mortar, the conservators realized that there was a deep crack on the extrados of the cupola with a SW-NE direction (fig.36), following the direction of the meridian, and affecting the upper parts of the corresponding drum windows (fig.37). The result of this inspection show that the crack is in evolution. At the moment it is impossible to take any major decision without knowing about the dynamics of the evolution, the distribution and the quantity of the opening of the crack. Only after analysis of this data (and this should be a general rule for the future: diagnosis before therapy) would it be possible to decide on the strategy which should be undertaken and particularly whether further strengthening is required. Due to the lack of information regarding the characteristics of the evolution of this phenomenon, it is difficult to evaluate if this could create a real danger situation. Under these circumstances, it was decided that the ring beam should be constructed. The construction of the reinforced ring was made on the base of the hemispherical dome, after the cleaning of the pre-existing material (mixed stones in mortar). The new construction retained the old (18th c.) wooden ring in place (fig.38), as well as the oak rafters (fig.39), which now were shortened. The old rafters and the load of the covering are now carried by the new reinforced ring however, without affecting the stone cornices.
(fig.40) – eliminating the main reason for the destruction of the cornices in the past. Taking into consideration the cleaning of the old material, the total weight of the new reinforced ring in its place doesn't seem fatal for the behavior of the cupola, adding only approx. 4 tones of weight to the walls (according to the calculations of the Georgian experts).

The cause of the main crack, as well as of the smaller ones, could be better clarified after the investigation already described above and after an appropriate structural analysis. In any case, and in relation to the results of the geotechnical report of the monument, we can say that the characteristics of the soil do not seem to have an influence on the settlements of the foundation of the church, and, accordingly, to the dome. It is more likely that the effects on the dome are due to seismic action, and in that case some specific research on the characteristics of this action (magnitude, intensity, epicentrum and frequency) should be done in the development of the project.

3. The cupola frescoes

The frescoes inside the dome date back to the 16th century and are particularly interesting: they have been executed under a kind of folkloric interpretation and with a “disarming” simplicity in execution, but also with a particular expressionism in the movements and immediacy in the expressions (fig.41, fig.42, fig.43, fig.44, fig.45, fig.46, fig.47, fig.48, fig.49). It is also noteworthy that they continue to follow the typical Byzantine iconographic programs and prototypes (note, for example, the face of Seraphim which imitates that of the pendentive of Haghia Sofia in Istanbul, recently cleaned) (fig.50, fig.51). Of course they are faced with serious conservation problems, for which competent experts have already expressed their opinion and recommendations.

Work in the interior of the cupola has started, filling the main cracking of the frescoes with injections (fig.52), and with grouting on the inner parts of the cracked window lintels.

4. Structural behavior assessment

4.1 General aspects

The Cathedral of Gelati, from a structural point view, appears to be a strong building (fig.53, 54).

In fact the geometrical shape and the walls, interconnected each other, have a kind of abutment effect. The result is a rigid body able to counteract the thrust of arches and vaults and the forces produced by the earthquakes.

This general aspect, however, doesn’t guarantee that the structure doesn’t present risks, considering the incertitude that we have today: the real efficiency of the connections between the walls and the other structural elements are not known; the effect of the deep decay which may reduce the strength of the stones and probably reduce the efficiency of the structural cooperation between the different elements is unknown, as well (fig. 55, fig.56, fig.57, fig.58, fig.59, fig.60).

4.2 The cupola (dome)

At the base of the cupola and at the connection with the drum, a ring-beam made of lime mortar (salt-free) was recently built, reinforced with stainless bars (fig.61, fig.62, fig.63, fig.64, fig. 65, fig.66, fig.67–A and Appendix – 3. Engineering Presentation).
The ring-beam has posed different questions and in particular has opened discussions on its ability to improve the safety level of the structure or, on the other side, to produce negative side effects.

From a cultural point of view, the ring appears compatible with the historic fabric of the building, being constructed in lime mortar and reinforced with stainless steel, and able to provide the required resistance.

From a structural point of view, the ring appears to be efficient, having at this level the concentration of the tensile circular strains produced at the base of the cupola. In this particular case these stresses are increased by the presence of the vertical cracks which interrupt the horizontal circular continuity of the construction, and which transfer the corresponded stresses to the base of the dome. The tension stresses are absorbed by the resistance of the reinforced ring. This circumstance gives an important role to the structural behavior.

The role of the ring-beam has, in any case, to be analyzed in the context of the dome-drum system. In fact the large windows of the drum reduce the bearing capacity considerably, in particular under seismic actions. It should be noted that in the past the western windows were closed with masonry of bricks / stones in mortar (fig.68). This closure has partially enhanced the carrying capacity of the drum of the dome. On the other hand the windows’ old wooden framing has been replaced with identical new one (fig. 69) – which substantially improved the atmospheric conditions inside the church and especially in the area of the dome.

The mission notes that a number of smaller vertical cracks have been detected around the upper level of the drum of the dome, both internally, on the mortar of the frescoes (fig.70, fig.71, fig.72) as well as externally, on the forehead above the arched lintels of window openings (fig.73). Therefore, the question arises whether these cracks can also be addressed by the reinforced lime-mortar ring already placed on the base of the cupola. According to the solution that was suggested and executed by the Georgian experts, vertical bars, incorporated into the body of the ring, are installed simultaneously by core drilling into the body of the cornice stones (approximately 5, to each peace) connecting both systems (fig.63, fig.64, fig.74) and increasing the stiffness of the cornice. In this way, in case of future seismic stresses, possible horizontal movements of the cornice stones would be prevented. Concerning the open joints and cracks on the window stone lintels (fig.37, fig.73), the mission does not think that further reinforcements to the upper part of the dome should be necessary. What is necessary instead is the local repair and consolidation of the stones, including injections and filling of the cracks.

Another important part is the connection between the base of the drum and the building underneath. This point must be analyzed because the horizontal shared forces are concentrated there, due to the seismic actions. The situation at this critical place is still unknown, as nothing has been uncovered yet there (fig.75, fig.76, fig.77, fig.78 and fig.67-D).

In the “Architectural rehabilitation of the Church of the Virgin (12th – 18th c.) at Gelati Monastery – Engineering Technical Report”, it is noted that many monuments in Georgia were strongly damaged after the Racha-Imereti earthquake, on April 1991 (p.12). It is worth underlying that the damages were concentrated mainly on the drums (as indeed one could expect judging from similar cases on medieval monuments in Greece and Italy).

4.3 The drum-dome system behavior
At this point, before discussing the safety problem, the mission considers it necessary to clarify what the structural behavior of the dome-drum system is.

The equilibrium of a dome is due to the two systems of stresses:

a. The principal system is represented by the meridians which work similar to a series of arches. The stresses are always compressed.

b. The secondary system is represented by the parallels (horizontal rings).

c. The stresses in the upper part of the parallels reach little values of compression, insignificant for the equilibrium. This behavior has made the removal of part of the upper structure possible, creating large oculus, as it in the Domus Aurea and Pantheon.

d. The stresses in the lower parallels of the dome, instead, are in tension and are essential for the stability of the dome. However, as the masonry has limited resistance on tension (resistance that could be reduced by cracks) it is clear that the base of the dome is the critical zone of the structure.

To eliminate the risks, often an annular chain (made of steel, wood, concrete etc.) or a small ring-beam is placed in this zone. The ring-beam already produced represents one of the possible reinforcements and, under this aspect, it is correct and justified.

5. Safety evaluation and proposals for the future

5.1 Criteria followed for the safety evaluation

To allow for a reliable judgment of the safety level, as clearly expressed in the “Recommendation for the Analysis, Conservation and Structural Restoration of Architectural Heritage”¹, it is usually necessary to follow three criteria:

1. historical research with particular reference to decay, damage and collapse under the effect of static and dynamic loads (as seismic actions) etc.

2. quantitative analysis based on mathematical models which represent only an approximate scheme of the reality

3. qualitative analysis based on observations of the building and on the comparison with similar structures

In the specific case of Gelati Cathedral, the mission can make the following considerations:

- Historical survey. The historical research has shown that the Cathedral has resisted well to earthquakes even if more precise information should be necessary.

  Attention must be paid, in any case, to the damage that is often created by earthquakes (cracks, deformations, decay…) which progressively reduces the resistance creating risky situations, unthinkable in a sound structure (as it has been the case of the Basilica of St. Francis of Assisi).

- Quantitative analysis. The mathematical models available today, allow for the detailed analysis of the stresses, and therefore provide a “precise” evaluation of

¹ Document proposed by the ISCARSARH and approved in Barcelona 2009 – attached here in Appendix
the safety levels. We have to remember, anyway, that these “precise” results of mathematical models do not correspond to the reality but only to a simplified scheme, because the reality itself is too complex to be known.

- Qualitative analysis. The qualitative analysis has the advantage to refer directly to the reality through the observation of the building, the study of drawings and of historical documents etc... On the other hand the analysis is influenced by the individual “expertise” and therefore has to be associated to the criteria already mentioned.

Regarding the Gelati Cathedral, it is interesting to consider the evidence of the analysis and differences in comparison with other big domes in architectural history (Appendix - I. Arches and Domes, and fig.9, fig.18, fig.19, fig.20, fig. 6)

- Analogies: the scheme which seems more similar to Gelati is the dome-drum of St. Peter (Appendix - I: Fig 14): the plan is square with four wall-pillars on the corners; four main arches then sustain the drum; four pendentives (triangular vaults visible also in Hagia Sophia – Appendix - I: Fig 7) complete the connection between the upper and lower structure. Concerning the general strength, the role that is given here to the walls in Hagia Sophia is due to buttresses (Appendix - I: Fig 6) and in Saint Mary of the Flower to little hemi-domes (Appendix - I: Fig 12). Concerning the drum, we observe that the geometry of Gelati Cathedral and of St. Peter’s (Appendix - I: Fig 14) is similar. In both structures the large windows reduce very much the bearing capacity even if in St. Peter the huge columns guarantee the strength.

- Differences: the main differences with St. Peter and Saint Mary of the Flower, with respect to Gelati, are the ribs and double cupolas which sustain a “lantern” on the top. The differences, anyway, do not influence significantly the bearing capacity.

5.2 Measures to guarantee safety conditions

The three different approaches to analyze the building, as already mentioned, globally show a well-built and apparently strong structure. Structural damage and material decay, however, can reduce considerably the apparent safety.

It is necessary, therefore, to organize a plan of actions to be undertaken in the short- and long-term.

The first phase includes a geometrical survey integrated with the individual analysis of each element in terms of material decay and structural damage. In this phase it is suitable to benefit from the scaffolding and workers on the site to organize a small “training yard”. The purpose is on the one hand to test the materials (as for example the injection of mortar in order to consolidate weak and damaged masonry) and on the other to evaluate the benefits and efficiency of the reinforcement work carried out as chosen samples on the damaged part of the structure. Mathematical models would contribute to the evaluation of the safety level of the present situation.

On the basis of this information, it would be possible to evaluate the costs of the restoration and reinforcement works.
The measures to be undertaken to guarantee safety conditions, detailed in a general project, are substantially of two kinds:

1. **Local interventions.** Reintegration of the damaged and deteriorated stones. This work should be done alongside the repair, consolidation and restoration of the wall surfaces and include, in case needed, local anchorages for recreating necessary continuity and strength for the limestone blocks.

2. **Global interventions.** Structural works on the basis of the results of the structural analysis, in order to ensure stability, durability and adequate protection under the effect of seismic forces.

### 5.3 The dome-drum system

Specific attention should be given to the dome-drum system. The two main problems are:

1. The vertical cracks on the dome modify the distribution of the stresses in the parallels. The stresses become zero in correspondence of the crack and increase in the adjacent zones. The effect of the ring-beam has to be seen also under this aspect. If necessary, its contribution can be improved by inserting, between the ring-beam and the base of the dome, a system of jacks able to produce supplementary horizontal radial inward forces (fig.79, fig.80, fig.81), pre-stressing, by this way, the dome (Appendix – 2. Seismic Behavior of Historic Buildings).

2. The large windows of the drum (fig.12, fig.18, fig.28, fig.75) produce a weak structure that may have problems under the effect of earthquakes, while the base of the drum seems to be the potential critical section. Structural calculations are therefore necessary in order to analyze the behavior of the drum and consequently design hypothetic reinforcements (fig.67-C, compare with Appendix – 2: 2.20).

### 5.4 The stone cornice (Appendix – 4. Dome Cornice Conservation Presentation)

The deterioration of the stone cornice is due to mechanical, as well as to atmospheric factors:

- Damage caused by the stresses under the direct contact of the old wooden rafters, owing to the movements of the latter under the air thrusts
- Damage caused by biological attack on the stone surface.

**Restoration of the stone cornice - Work currently being carried out**

1. Shortening of the existing wooden rafters
2. Treatment of stone surface against biological attack
   - Cleaning the outer surface of the cornice by means of spraying
   - Cleaning the outer surface of the cornice by using carefully mechanical methods
3. Reconstruction of cornices with stone
   - Preparing the holes for anchoring
- Preparing the new stone slabs
- Anchoring the stone with stainless steel horizontal bars
- Fixing the new stone slabs

iv. Reconstruction of damaged cornice parts with lime mortar:
- Reconstruction of cornice with lime mortar – filling by hand the missing small parts of the original stone cornice and shaping the new final surface of the cornice
- Injection process – filling the empty space between the wooden ring and the stone cornice (old and new parts)

Remarks

The restoration work taking place at the level of the stone cornice of the drum is careful and systematic. It should be emphasized that the filling-out of the large missing parts is being carried out using stone slabs of width equal to the edge of the original cornice, while the damaged parts are filled with a suitable mortar by hand (fig.82, fig.83, fig.84). This is to say that there isn’t a full replacement of the missing parts, but a “refurbishing of the current forms of decay and surface deterioration”\(^2\) and a restoration of the continuity and the stability of the cornice to the upper level. Following this method, the missing gaps are complemented to the extent that the intervention preserves and protects the existing situation with the “injuries” on the body of the cornice. One must bear in mind that, in principle, the monument should highlight its historical condition and not be reconstructed in detail.

The same method has started to be applied for the restoration of the damaged cornice of St. George church (fig.85, fig.86, fig.87)

5.5 Glazed roof tiles

The archaeological excavations around the monument proved that originally the dome was covered in glazed tiles (greenish-turquoise, light blue, green and light brown colors), so the specialists decided that the tin roofing of the complex churches should be replaced by relevant glazed tile roofing. The experience of the traditional coloring composition, the layer-applying technique, and the old firing technology were obtained after long-term research and experimental work: a) the palette of colors, implying for each tile not just one color, but a whole range of colors achieved by means of natural pigments with iron and other admixtures (fig.88), and b) greater transparency of the colors, distinguishing the Georgian glazing technique from the Asian one. Consequently, each tile used in the monastery complex is produced manually, while 7 main and 6 additional different elements were elaborated.

The method (with green-tone glazed tiles) was first applied to replace the tin roofing of the two-storey St. Nicolas church (fig.89), in front of the Cathedral, and after that to the roofing of the side bell tower (fig.90), and that of St. George church (fig.91) - with excellent results.

\(^2\) Stefano Volta, Methodology report about conservation of building stones of the Early 12th-Century Church of the Virgin at Gelati Monastery in Kutaisi, p.3
The ICOMOS representative had the welcomed possibility to visit the laboratories of the Tbilisi State Academy of Fine Arts where he was informed about the activities of the Laboratories for the cleaning and conservation of the icons (fig.92), as well as for the analysis of the bio-deterioration of building materials. He then visited the private clay atelier producing the glazed tiles, where he was informed in detail about the procedure (fig.93, fig.94, fig.95, fig.96, fig.97, fig.98).

6. Further remarks regarding the Master Plan

Additionally to the discoveries to the north side of the Academy building (warehouses with big clay jars, ground water runoff channels and underground tunnel communication), the excavation works near the south gate of the monastic ensemble are continuing, bringing to light new archaeological finds of great interest (fig.1 – the marked area):

a) A tomb of an unknown historical personality, right to the south gate of the complex (fig.99), underlines even further the importance of the ancient entrance.

b) Many parts of the old cobbled path, leading from the city of Kutaisi to the monastery.

c) Next to the south gate, an even earlier gate was found, guarded by a pair of cylindrical towers, together with the old (lower) level of the monastery grounds pavement (fig.100, fig.101).

In the mission’s opinion, the above new findings dictate:

a) The disclosure, to the greatest possible extent, of the old cobbled path with a plan for its future use as a hiking route between the monastery and the city.

b) The careful disclosure, to a larger extent, of the old pavement of the monastery courtyard; the old pavement should be related to the future Master Plan of the ensemble, taking into account the existing (higher) levels of the entrances to the historic buildings.

Finally, the mission considers that special attention should be devoted to the careful conservation of the perimeter defense wall of the monastery complex, built in solid stone blocks and maintaining the traditional building methods, as one of the main characteristics of the old, external appearance of the monastery ensemble (fig.102, fig.103).

RECOMMENDATIONS

The State Party is invited to address the following recommendations:

1) Undertake a detailed inspection of the base of the drum.

2) Undertake a geometrical survey integrated with the individual analysis of each construction element in terms of the material decay and structural damage. In this phase it is suitable to benefit from the scaffolding and workers on the site to organize a small “training yard”. The purpose is on the one hand to test the materials (as for example the injection of mortar in order to consolidate weak and damaged masonry) and on the other to evaluate the benefits and efficiency of the reinforcement works carried out as chosen samples on the damaged part of the structure.

3) Prepare mathematical models to evaluate the safety levels of the present situation, including a static model of the dome-drum system.
4) Local interventions: Reintegration of the damaged and deteriorated stones; This work should be done alongside the repair, consolidation and restoration of the wall surfaces and, in case needed, include local anchorages for recreating necessary continuity and strength for the limestone blocks.

5) Global interventions: Structural work on the basis of the results of the structural analysis, in order to ensure stability, durability and adequate protection under the effect of seismic forces.

6) For the new roofing arrangement, ensure the protection of the vaults and walls, preventing leakage into the foundation and the gravel layer as well as rainwater from splashing back on the walls, and restoring the appearance of the building.

7) Repair the old rainwater drainage system around the foundations of the church and put into operation.

The measures proposed above will significantly improve the state of conservation of the church and preserve the authenticity of the building.

In addition, the State Party is recommended to

8) Undertake a historical analysis of the seismic action of the micro-zoning of the region of the monument, including the systematic recording of the characteristics of this action (magnitude, intensity, epicentrum and frequency) and the relevant results. On the basis of this data - the creation of a kind of "personal" folder for the monument, which should receive input and be constantly updated with new data, and with eventual results from future historical research.

9) As an absolute and immediate necessity, establish a permanent monitoring system on the dome of the church. This can be done with contemporary methods (as presented in Appendix – 2. Seismic Behavior of Historic Buildings), allowing for the continuous monitoring and recording of the behavior of the sensitive areas of the monument from the level of the ground floor.
ANNEX I
TERMS OF REFERENCE

for the ICOMOS advisory mission to WH property Bagrati Cathedral
and Gelati Monastery (Kutaisi), Georgia,
21-25 January, 2015

The ICOMOS expert will be asked to interact with the Ministry of Culture, National Agency for Cultural Heritage of Georgia, and all other key stakeholders and experts involved in the ongoing conservation works in Gelati monastery, and carry out the following tasks:

a) Review existing documentation on the ongoing works in the Gelati Monastery in Georgia.
b) Provide an opinion on the overall structural stability of the complex.
c) Provide an opinion on the static and dynamic implications, as well as the construction techniques, of the beam recently built at the top of the drum of the main church of the complex, made of lime mortar reinforced with steel bars, anchored with steel bars to the existing stone structure. This should include an advice on either removing or endorsing such beam.
d) Provide an opinion on alternatives structural interventions to such beam, should it be considered a not opportune intervention.
e) Provide an opinion on any other structural intervention to enhance the seismic resilience of the complex.

TERMS OF REFERENCE

for the WORLD BANK EXPERT advisory mission to WH property Bagrati Cathedral
and Gelati Monastery (Kutaisi), Georgia,
21-25 January, 2015

The Consultant will be asked to interact with the National Agency for Cultural Heritage of Georgia and carry out the following tasks:

a) Review existing documentation on the ongoing works in the Gelati Monastery in Georgia;
b) Provide an opinion on the overall structural stability of the complex;
c) Provide an opinion on the dynamic implications as well as the construction techniques, of the beam recently built at the top of the drum of the main church of the complex, made of lime mortar reinforced with steel bars, anchored with steel bars to the existing stone structure. This should include an advice on either removing or endorsing such beam;
d) Provide an opinion on alternatives structural interventions to such beam, should it be considered a not opportune intervention;
e) Provide an opinion on any other structural intervention to enhance the seismic resilience of the complex.

ADVISORY MISSION PROGRAMME
Wednesday, 21 January 2015: Evening - Arrival of ICOMOS expert in Tbilisi and accommodation

Thursday, 22 January 2015
1. Working meeting at the National Agency for Cultural Heritage Preservation of Georgia. Discussion on the state of conservation of Gelati monastery World Heritage property. Presentation of the Project for the Rehabilitation of the Cathedral and particularly the “Engineering technical overview” and the “Dome Cornice Conservation” by the working team. Presentation by ICOMOS representative aspects of the Soil settlements and historic buildings.
2. Lunch offered by the Ministry of Culture, Monuments Protection and Sport of Georgia.

Friday, 23 January 2015
Departure from Tbilisi to Gelati
1. Visit to Gelati Monastery and inspection of the Cathedral and particular of the cupola, accompanying by all key stakeholders and experts involved in the conservation works. In situ discussions.
2. Visit to the excavations and the other ongoing works in Gelati Monastery.
Lunch in Kutaisi offered by the Georgian Arts and Culture Center.
Departure to Tbilisi

Saturday, 24 January 2015
1. Debriefing meeting at the Offices of the South Caucasus Department of World Bank.
2. Presentation of the “Arches and Domes” by Prof. Giorgio Croci.
3. Presentation of the “Seismic Behavior of Historic Buildings” by Prof. Alkiviades Prepis.
4. Presentation of the “Stone conservation project” for the Cathedral by Prof. Nana Kuprashvili. Discussions.
Lunch offered by the South Caucasus Department of World Bank.
5. Joint work of the two experts for the common Report, including observations, findings and proposals on the work on the Cathedral dome (G. Croci and A. Prepis)

Sunday, 25 January 2015: Departure

PERSONS MET DURING THE MISSION:
1. Mr. Levan Kharatishvili, Deputy Minister of Culture and Monuments Protection of Georgia
2. Mr. Nikoloz Antidze, Director General of National Agency for Cultural Heritage Preservation of Georgia
4. Mrs. Maka Dvalishvili, President of Georgian Arts and Culture Center, Project team leader
5. Mr. Ahmed A. R. Eiweida, Sustainable Development Sector Leader for South Caucasus Department of World Bank
6. Mr. Kakha Trapaidze, Tbilisi State Academy of Fine Arts, Project scientific leader
7. Mr. David Michelmore, Consultant expert for World Bank project for Gelati monastery
8. Mrs. Rusudan Mirzikashvili, Head of the UNESCO and International Relations Unit, NACHPG
9. Mrs. Nana Kuprashvili, Tbilisi State Academy of Fine Arts, Department Restoration and Art History, Chief of Laboratory, Scientific leader of the stone and frescoes conservation of the project
10. Mr. Alexander Rubashvili, Head of the restorers group, the restoration firm “Gorso”
11. Mrs. Tamar Lilukashvili, Tbilisi State Academy of Fine Arts
12. Mr. George Sosanidze, Architect restorer, Head of the Monuments Rehabilitation Design Unit, NACHPG
13. Restorers’ group: Mr. Tengiz Gabunia, architect-restorer; Mr. George Kotetishvili, architect-restorer; Mr. George Gagoshidze, Art Hisotrian
14. Mr. George Tchanukvadze, Chief constructor engineer of the project, Permits and Ongoing Projects Unit, NACHPG
15. Mr. David Ramishvili, Engineer, Tbilisi State Academy of Fine Arts
16. Mr. George Khurtsilava, Engineer, Construction engineering firm “Ikorta”
17. Mrs. Mariam Didebulidze, Director of the George Chubinasvili National Research Centre for Georgian Art History and Heritage Preservation
18. Mr. Roland Isakadze, Manager of the Kutaisi Historical-Architectural Museum–Reserve
19. Mr. Shalva Buadze, Specialist, Kutaisi Historical-Architectural Museum–Reserve
20. Mrs. Courtney E. Austrian, Public Affairs Officer, United States Embassy
21. Mrs. Molly A. Rydzynski, Cultural Affairs, United States Embassy
22. Mr. James Dewey, Cultural Affairs Officer, United States Embassy
23. Mr. Genady Ekizasvili, ceramist, head of the ceramic laboratory
24. Mrs. Maia Gabadadze, ceramist
ANNEX II

ILLUSTRATIVE DOCUMENTATION

(See attached ZIP file)

Fig. 1: Axonometric plan of the monastic complex with indication of the area of the new archaeological discoveries

Fig. 2: The monastic complex churches:
- Holy Mother Birth main church (katholikon, 1106), in the middle
- St. George church (XIII century), to the right
- St. Nikolas church (XIII century), to the left

Fig. 3: View to the west part of the monastery grounds

Fig. 4: The cast iron and steel door, the booty brought by Demetre I (1125-1155) from the Ganja fortress

Fig. 5: View of the Cathedral church from south

Fig. 6: Plan of the Holy Mother Birth main church (katholikon) in Gelati Monastery

Fig. 7, Fig. 8: Frescoes in the interior of the main church

Fig. 9: The hemisphere of the bema apse is covered by mosaic masterpieces. A similar hemi-dome is to stabilize the dome of Hagia Sophia (see Appendix – 1. Arches and Domes)

Fig. 10: The crepidoma of the church with the old drainage system around it

Fig. 11: Detail of the upper western part – view from south

Fig. 12: Plan of the eastern façade with indications of the damages and restoration works

Fig. 13: Facing masonry to the tin covering - existing condition

Fig. 14: N-E corner of the apses of the church with long-term masonry damages caused by the rain and wind

Fig. 15, Fig. 16, Fig. 17: Details of the existing condition of the stone cornice

Fig. 18: The cupola of Holy Mother Birth church – condition before starting the architectural rehabilitation works

Fig. 19: The western part of the Cathedral with two-storey lateral compartments

Fig. 20: Naos with the cupola and eastern part of the Cathedral with two-storey parabemata (Prothesis and Diakonikon). View of the arches and pendentives that connect the arches with the dome

Fig. 21: Cross section plan of the cathedral

Fig. 22: The cupola of Ishkhani church (10th - 11th c.) – contemporary Turkey

Fig. 23: The cupola of Khakhuli church (second half of the 10th c.) – contemporary Turkey

Fig. 24: The top of the wooden frame on oak beams, which gave the conical shape of the dome

Fig. 25: The rafters of the oak frame, which gave the conical shape of the dome

Fig. 26: The scaffolding in the interior of the church up to the dome. Interior view of the system of pillars-arches-domes. On the lower part the bema hemi-dome is visible, which stabilizes the dome. This configuration is very similar to the dome of St. Peter (see Appendix – 1. Arches and Domes)

Fig. 27: The scaffolding inside the drum of the cupola

Fig. 28: The windows on the drum of the cupola
Fig. 29: The main crack on the frescoes, widened along the cupola meridian

Fig. 30, Fig. 31, Fig. 32: The main crack continuing on the semicircular lintels of the drum windows

Fig. 33, Fig. 34: Opening of the wooden roof: the wooden frame with the old oak rafters and the newer roof sheathing

Fig. 35: Interior of the wooden roof: the old oak rafters and the base of the dome

Fig. 36: The deep crack on the extrados of the dome

Fig. 37: Cracks on the arched lintels of tympanon windows

Fig. 38: The construction of the reinforced ring retained the old (18th c.) wooden ring in place

Fig. 39: The extrados of the stone cupola, with the retained old oak rafters and the new wooden covering

Fig. 40: Interior of the perimetric corridor with the new reinforced ring. The old oak rafters are fixed on the reinforced ring and not on the old wooden one (preserved in the site), without affecting the stone cornices.

Fig. 41: The monitoring team on the top of the interior scaffolding, just under the cupola

Fig. 42: (Christ Pantocrator), Fig. 43 (King Solomon), Fig. 44, Fig. 45 (Prophets), Fig. 46 (Angel), Fig. 47 (the Epitaph), Fig. 48, Fig. 49 (Angels) - Details of the frescoes on the cupola interior surface

Fig. 50: Seraphim – Detail of the frescoes on the cupola interior

Fig. 51: Seraphim - mosaic depiction on the pendentive of Hagia Sofia in Istanbul, recently cleaned

Fig. 52: Filling-up, by injections, the main crack on the cupola frescoes

Fig. 53: General view of the Cathedral of Gelati from the north - the system of walls-abutments interconnected each other to ensure a monolithic behavior

Fig. 54: The upper part of the Cathedral – view from the S-E

Fig. 55: Deep decay which influence the structure, as well

Fig. 56, Fig. 57, Fig. 58: Disconnection between the blocks of a wall and alteration of the structural behavior

Fig. 59: Northern façade of the narthex, under the old covering - disconnection in the blocks of arches

Fig. 60: Upper part of the exterior walls with decorative arcades, ending to the cornice - disconnection in the blocks of arches

Fig. 61, Fig. 62: The construction of the ring-beam at the base of the dome, realized with lime mortar (salt-free) and reinforced with stainless steel bars

Fig. 63, Fig. 64, Fig. 74: Vertical bars, incorporated into the body of the ring, are installed simultaneously by core drilling into the body of the cornice stones, connecting both systems

Fig. 65: The new ring construction retained the old (18th c.) wooden ring in place, while shortened the old oak rafters

Fig. 66: The situation on the dome base and cornice before and after the construction of the reinforced ring and the new roofing with the glazed tiles

Fig. 67: The cupola - position of the established ring and hypothetical additional reinforcing

Fig. 68: The western windows of the drum, closed with masonry of bricks / stones in mortar
Fig. 69: New windows wooden framing, replaced the old one

Fig. 70, Fig. 71, Fig. 72: Vertical cracks detected around the upper level of the drum, on the frescoes

Fig. 73: Cracks on the arched lintels of drum windows

Fig. 74: Vertical bars, incorporated into the body of the ring, are installed simultaneously by core drilling into the body of the cornice stones, connecting both systems

Fig. 75: The drum of the cupola - the large windows reduce substantially the resistance of the drum

Fig. 76: The base of the drum

Fig. 77, Fig. 78: The connection between the base of the drum and the building underneath

Fig. 79: Proposed jacks for pre-stressing the dome

Fig. 80: Presentation by Prof. Giorgio Croci of the jacks that could be inserted to pre-stress the dome

Fig. 81: Presentation by Prof. Alkiviadis Prepis of the seismic behavior of the dome-drum system

Fig. 82, Fig. 83, Fig. 84: Restoration of the stone cornice: the filling-up of the large missing parts is made by fixing stone, by stainless steel bars, with width equal to the edge of the original cornice, while the wounded parts are filled with a suitable mortar by hand

Fig. 85, Fig. 86, Fig. 87: Restoration of the damaged cornice of St. George church

Fig. 88: New glazed tiles, made according to the original ones, in place for the covering of the Cathedral roofing

Fig. 89: The two-storey St. Nicolas church in front of the cathedral - the restored roofing with glazed tiles

Fig. 90: The bell tower - the restored roofing with glazed tiles

Fig. 91: St. George church cupola - the restored roofing with glazed tiles

Fig. 92: ICOMOS representative visiting the laboratories of the Georgian Arts and Culture Center (cleaning and conservation of icons)

Fig. 93: ICOMOS representative visiting the clay atelier for producing the glazed tiles

Fig. 94, Fig. 95, Fig. 96, Fig. 97, Fig. 98: Pictures from the process of the production of the glazed tiles for the restoration of the church roofing

Fig. 99: A new discovered tomb of an unknown historical personality, to the south gate of the complex

Fig. 100, Fig. 101: The earlier gate, found next to the south gate, guarded by a pair of cylindrical towers

Fig. 102, Fig. 103: The perimetric defense wall of the monastery complex, built by large stone blocks

Fig. 104, Fig. 105: The members of the mission together with the contributors of the meetings and on-site examination of the monument
APPENDIX

(See attached PDF)

1. Arches and Domes (Giorgio Croci)
2. Seismic Behavior of Historic Buildings (Alkiviades Prepis)
3. Engineering Presentation
4. Dome Cornice Conservation
5. ICOMOS Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage
2.1 Foreword

The arch has probably been the most important innovation in the history of architecture, transforming, thanks to the curvature associated with the thrust at the springs, bending moments in compression forces, even if a certain bending strength is indispensable to maintain a stable shape.

Spatial vaults and in particular the dome are a development of the arch concept. Their particularly satisfactory behaviour is due to the double curvature and mainly to the hoop effect of horizontal rings. The dome of the Domus Aurea (I century A.C.) is the first important example (fig. 1).

The cooperation between the forces that flow through the meridians and the parallels allows to reach exceptional resistance.

This give the possibility to choice different architectural shapes even when these are not the most rational and efficient one from structural point of view, as in the case of the Bulbous domes in Islamic countries (fig. 2).

Similar to the arches, in dry stone structures, the inclination of the joints influence the shape. In Asian architecture where the joints are usually horizontal, domes are transformed in a kind of towers due to the necessity of increasing the vertical forces in order to reduce the shear forces and therefore the risk of sliding between joints (fig. 3).

Figure 1 - The Octagonal Dome in the Domus Aurea
2.2 THE PANTHEON

The Pantheon (built under the Emperor Adriano in the 2nd century A.C. – fig. 4) is made of a cylinder (the Rotunda) and a hemispheric dome of the same diameter (around 43 m).

As already shown in the Domus Aurea, the top of the dome is not indispensable for equilibrium letting the possibility of a large “oculus”.

The cylinder (drum or rotunda) appears as a big brick wall, containing within its thickness a series of arches which inside correspond to niches and empty spaces.

Probably the builders of the Pantheon were influenced by the Coliseum which, even if it appears completely different in its structure, in reality it is much similar to the Rotunda than one would expected (fig. 5).
2.3 HAGIA SOPHIA
Hagia Sophia (built in the present shape under the Emperor Giustiniano in the 6th century – fig. 6) chronologically is the second biggest dome in the history of architecture and got its inspiration from the Pantheon. However, Hagia Sophia features some important differences related to the fact that the dome is supported by four huge pillars placed on the corners of an ideal square base (32 meters). Two problems arise:
- how to resist the circumferential forces at the border of the dome;
- how to transfer the vertical forces from the meridians to the pillars.

The solution of the first problem was the introduction of hemidomes and abutments to balance the thrusts while “pendentives” on the four corners, associated with arches, have solved the second issue, allowing the forces to flow from the top to the ground (fig. 7).

These innovations turned to be very important; most of the following domes are inspired on these principles.

Hagia Sophia suffered for several earthquakes. The first one took place just as the construction was completed and produced large collapses. The cupola was immediately
rebuilt. The second major collapse, in the 10\textsuperscript{th} century, involved the Western portion of the building with the arch and a quadrant of about 140° of the dome. This part was rebuilt in the following years. The third collapse took place on the 14\textsuperscript{th} century and produced a collapse, similar to the former one, on the opposite side.

![Figure 6 - Hagia Sophia in Istanbul](image)

![Figure 7 - Dome, arches and pendentives in Hagia Sophia](image)

### 2.4. THE TEMPLES OF ANGKOR

Angkor is an extraordinary site where ancient temples (built between the 9\textsuperscript{th} and 13\textsuperscript{th} century A.C.) emerge from the tropical forest that has gradually overrun them through the centuries. Angkor Wat, built in the 12\textsuperscript{th} century, is the masterpiece of Khmer art (fig. 8). The temples have a typical tower shape that is the consequence not only of the Khmer architecture, but also (and perhaps mainly) of the need of stabilising with its huge load, the structure, built with sandstone blocks and horizontal joints.
2.5. THE BASILICA OF ST. FRANCIS OF ASSISI

The Basilica of St. Francis of Assisi was built in the 13th century (fig. 9). It suffered several earthquakes, but none produced a damage as great as that which hit the Basilica on September 26, 1997 producing the collapse of two vaults (fig. 10), large cracks everywhere and the collapse of the tympanum of one transept. Urgent measures, to prevent large collapses, were required on the vaults. Some synthetic fibre strips where applied on the vaults over the cracks and a system of wires and springs to suspend the vaults to the roof was executed as well. The first works have been the reconstruction of the collapsed the vaults by using as much as possible the original salvaged bricks. With reference to the large cracks and the permanent deformations, that generally affected the vaults, it was decided to build, over the extrados, a net of ribs made of timber strips covered with a fabric of aramidic fibres and epoxy resin (fig. 11).
2.6 SAINT MARY OF THE FLOWER

The dome of the Church of St. Mary of the Flower (Brunelleschi, 15th century – fig. 12) is the first example of a big dome with a double shell on an octagonal plan. The dome, having a diameter 43 m similar to the Pantheon, received its inspiration from the Gothic vaults. In order to reduce the thrust the shape is ogival and to reduce the weight the main bearing structure is made of 8 principal ribs in the corners. The circumferential connection is ensured by 4 stone ribs (a kind of “chains of stone” reinforced with steel clamps) and a wooden chain;

The octagonal shape of the dome, proper also of drum and plan of the church underneath, lets reasonably imagine that seismic behaviour with, as already said, the “stone chains” or supplementary steel chains are able to provide tensile strength. Some small cracks visible on shells, in the zones over the windows, appear to be related more to the phase of construction than to seismic effects (which, on the other hand, are very low in Florence).

The octagonal base of the dome is made of four huge pillars on four sides and four arches in between so that the supporting structure is stiff (fig. 13), and even more stiffened by the connection with small hemidomes, probably inspired by Hagia Sophia.

On the top of the dome over the anular ring at the border of the oculus, there is a lantern.
2.7 ST. PETER
The dome of St. Peter (Michelangelo 16th century – fig. 14) has a diameter similar to the Pantheon and S. Maria del Fiore (43 m) and, as the last, has deeply been influenced by the Gothic conception. Nevertheless a general harmony and classical inspiration is evident. The project of the St. Peter’s dome has had several vicissitudes before arriving at the final design of Michelangelo.

A significant difference between the domes of Brunelleschi and Michelangelo is in the shape of the drum, that here is circular, even if the dome is made with 16 ribs. The circumferential stone chains of S. Maria del Fiore, in St. Peter are replaced with steel chains.

From seismic point of view there are certain analogies between the structural scheme of Hagia Sophia and S. Peter. As in both cases the forces are obliged to flow from the circular plane of the dome to the four columns placed on the corners of an ideal square, through four arches and relative pendentives.

The substantial difference however is that in St. Peter there is a strong drum.
St. Peter (16th century) represents the last exceptional dome ever built, having a diameter of around 42 mt., as already said, is similar to the Pantheon, Hagia Sophia and St. Mary of the Flowers.

In the following centuries these performances have never been reached again, even if the dome St. Paul in London (17th century) (fig. 15) and the dome of the Pantheon in Paris (18th century), both built with three vaults (diameter around 34 mt.), represent interesting solutions. However, the strong identification between structure and architecture that has characterised the previous domes, appears to be lost: it is only the intermediate shell to provide the structural bearing capacity, while the inner and external vaults have mainly a decorative purpose.

The development of new techniques and technologies has transformed the static conception of the vaults, and steel begins to be preferred to masonry even if these steel structures are often hidden under a masonry casing; this is the case of the dome of the Capital in Washington (fig. 16) built in the 19th century, where a steel reticulated dome is covered with blocks of stones.

The reconstruction at the end of the 20th century of the dome of Reichstadt in Berlin (fig. 17), destroyed during the last world war, is an interesting example of the use of steel that doesn’t need to be hidden, but on the contrary, shows all its exceptional static and architectonic possibilities.

Last but not the least, we would like to mention the Millennium Dome (fig. 18) built to celebrate the passage between the 20th and the 21st century, so huge that today nobody exactly knows how to utilise it. Probably it will be dismantled.
Figure 15 - St. Paul Cathedral in London

Figure 16 – The dome of the Capital in Washington
Figure 17 – The Reichtstadt dome in Berlin

Figure 18 – the Millennium Dome
Seismic Behavior of Historic Buildings

Prof. Dr. Alkiviades Prepis

Earthquake events in Constantinople, according to Hermann Gall, in 1556
Soil Settlements and Historic Buildings

Haghia Sophia Cathedral in Istanbul presents steep inclination of its bearing structural elements due to soil settlements, because of seismic actions.
St. Andrew church (1747-1754) in Kiev, Ukraine (2009). Built by Bartolommeo Rastrelli, is a notable example of Baroque architecture, and its location on top of the Kievan mountain made it a recognizable monument of the city.
Underpinning with jet grouting columns of St. Andrew Church in Kyiv (Ukraine) to address the collapse of the hill soil.
Earthquakes and Historic Buildings

Fig. 1. Epicenters of all known strong (M≥6.0) earthquakes that occurred in the Mediterranean area during 1901-2002.

Fig. 5. Plate motions which affect active tectonics in the Aegean and surrounding area (modified from Papazachos et al., 1997).

Some of the causes leading to the weakness of the Monument

Instrumental Seismicity

SEISMICITY IN GREECE 1900 - 2006

Weakness chart during time of Historical Building
The archipelago of Santorini is worldwide unique phenomenon of a volcano caldera. The crescent which is called Santorini, Thirasia and Aspronisi form a circle in the middle of which there is the caldera of Santorini, the largest in the world.
Construction method of traditional houses in Santorini
The Thera volcano active in a lithography of 1866

The eruption of 1950

Damage to houses by the earthquake of 1956
Nea Kameni and Palea Kameni were formed by underwater eruptions and they are the latest pieces of land in the Mediterranean.

The Akrotiri excavation site is of a Minoan Bronze Age settlement on the Greek island of Santorini, associated with the Minoan civilization. Akrotiri was buried by the widespread Theran eruption in the middle of the second millennium BC (during the Late Minoan IA period); as a result, like the Roman ruins of Pompeii after it, it is remarkably well-preserved. Frescoes, pottery, furniture, advanced drainage systems and three-story buildings have been discovered at the site.
Historians and archaeologists appear puzzled as to the date that exploded the volcano of Thera, with probable date somewhere between 1645 and 1500 BC.
The region of Crete (Greek bow), meeting place of the tectonic plates of Africa and Eurasia, is perhaps the most seismic zone of Europe. In 365 AD a tectonic paroxysm raised the west end of the island at 6-9 m., while precipitated the eastern end at 2-4 m.

The extensive use of wooden beams in the walls of prehistoric Knossos palaces was made for antiseismic reasons.
The extensive use of wooden tie-beams in the walls of the Byzantine churches in the Balkans was made for antiseismic reasons.
The extensive use of wooden tie-beams in the walls of the traditional buildings of the Balkans was made for antiseismic reasons.
Earthquakes and Historic Buildings

Obelisk of Theodosius I in Istanbul
The arrows show the different alignments of the putlog holes on each section of the wall, clearly built as two different parts; the resulting joint purposively has no toothing.

Northeast supporting wall. Construction joint with no toothing between the section of the wall supporting the barrel vault and part support of the spring cross vault located on top of the entablature.
Bayezid II complex in Edirne, Turkey - 1488
The Freyssi Flat Jack is a thin hydraulic jacking device used in Civil and Structural Engineering work to exert large forces simply and economically. Originally developed by Eugene Freyssinet as a means of prestressing concrete under unusual circumstances, its field of application has now extended far beyond this sphere.

Simple and compact, Freyssinet Flat Jacks are often used for remedial measures or structural extensions as well as for new construction. The Freyssi Flat Jack can be used to solve a large variety of engineering problems:

- Control of thrust forces
- Adjustment of support reactions
- Structural lifting
- Load measurement

- Prestressing between abutments
- Structural pre-loading
- Underpinning
- Thrust maintenance

Figure 5.39 - The enlargement of the foundations and the jacks to compensate for the deformations.

Figure 6.5 - Central tower foundations, York Minster, England (Courtesy: Ove Arup & Partners)

Section through north-west pier foundation. The existing masonry was continued with the new concrete. The flat-jacks were slowly inflated to press each of the two equalizer loads carried by old and new work.
The National Museum of Western Art was designed by Le Corbusier in 1959 and isolation retrofitted in 1998. The retrofit involved the placement of 42 high damping rubber bearings below the original spread footing foundation system. Shake table testing was done to verify the dynamic behavior of the expansion joint system utilized in the retrofit.
Figure 9 Reform work of mid-story isolation
The monastery is sited in a neogene tectonic graben between the mountains Egaleo and Korydallos, at the west side of the basin of Athens. The church was built in 11th c. AD, replacing an older one. Large-scale damages are reported in the 13th c, and an overhaul took place in the 14th c. Extended damages occurred during the latest Athens earthquake (September 7th, 1999). To the right: the iron construction for reinforcing the pillars between the widows openings.
Since 2012 is operating a Geological Station for monitoring seismic activity, established to the foundations of the cathedral of Charlemagne in Aachen (approx. 800).

Monitoring the behavior of cracking - “telltelers” / sensors

Hagia Sofpha, Istanbul - modern sensors and checkpoints opened by Mimar Sinan in the 16th century.
Selecting a gauge depending on the type of crack or distortion
Western façade of Parthenon: sensors of optical fibers for measuring deformations of the columns that are expected after discharge them from the metopes load.
Architectural Rehabilitation of the Church of the Virgin (12th-18th) at Gelati Monastery

Engineering technical overview
The Church of the Virgin In Gelati Monastery

Studies conducted

• Geological Studies
• Archeological Studies
• Art Historical Studies
• Engineering Studies
• Architectural Measurements
• Mural paintings
• Stone conservation
Geological studies

Geological studies have been conducted in 2 phases: 1\textsuperscript{st} in 2004 and 2\textsuperscript{nd} in 2008

On the first stage have been done 7 pits;

On the 2\textsuperscript{nd} – 31 pits;

The study showed that the main church has a strip foundation, built by rough stone on the lime mortar and lays on the dolomitized limestone. Both stone and lime mortar strength characteristics are satisfactory.
Archaeological studies

Archaeological studies have been conducted in 2007-2010. Have been done 14 pits.

During the study revealed that the original roofing was made by the glazed ceramic tiles. On its result have been elaborated the configuration of the roofing and color of the tiles.

Elaboration of the Master plan of the site had also been based on the study results.
Art  Historical study
The study is dedicated to the research of the roofing of the main church in Gelati Monastery. It investigates the historical sources and archeological material due to which different layers of the roofing have been determined:

• 12th-14th c dark green glazed ceramic tiles.
• 13th c stone slabs, which covered St. Marine chapel
• 16th c light blue glazed ceramic tiles
• Copper roofing (mentioned in the literary sources of 1650-1652.
• Wooden roofing (mentioned in the literary sources of 1772)
• Tin roofing (mentioned in the literary sources of 1772)

The visual inspection of the Dome roofing revealed presence of the well preserved oak beams from 19th c.
Engineering study

Engineering-technical study envisaged opening, probing and visual examination of the roofing. It revealed that significant crack was present in the south-east part of the dome, which reaches the arch of the drum window opening. The particular crack had been documented and filled by the lime mortar in 90-ins of 20th c.

The main problems revealed:

1. The scaffolding in the interior enabled project team to investigate the crack. The close examination revealed that the crack is in dynamic and the additional cracks had been formed in the filling process.
2. The cornice stones are cracked. which is mainly caused by the direct contact of wooden rafters during the wind.
Works conducted

• To avoid further deformation and to retain the dome steadiness, the arrangement of the dome supporting belt on the level of the dome bottom was decided. The belt also serves as a supporter of wooden rafters which are anchored in the belt. This reduced the pressure on the concise stones.
• Stainless steel bars, lime and washed out gravel were applied as a material;

• The construction of the belt was based on the preliminary calculations

• The rafters had been fully covered by the oak boards,

• The hydro isolation was arranged above the wooden boards and were prepared for the arrangement of ceramic tiling
Stone conservation and Rehabilitation of Concedes

Conservation of the Mural Paintings in the Dome
Dome Cornice Conservation

Church of the Virgin at Gelati Monastery
DETERIORATION OF THE STONENES ON CORNICE

Fig. 1 biological attack

Fig. 2 detached part of the stone

Fig. 3 damage caused by direct contact with the old rafters.
• Shortening of the existing wood rafters;
• Biological Treatment of the stone surface;
• Reconstruction of cornices with stone;
• Reconstruction of cornice with lime mortar;
• Injection;

• ჩატარებული სამუშაოები:
• ბიოლოგიური სამუშაოები;
• შეწყვეტა ხელშეკრულები;
• არენტანა დამოკლები;
• ბიოლოგიური მოშორება;
• ექსტრექტირება
SHORTENING OF THE EXISTING ROOF RAFTERS

Fig. 1 Rafters before the shortening

Fig. 2 Damage caused by the rafters

Fig. 3 Rafters after the shortening
RECONSTRUCTION OF CORNICE WITH STONES

Fig. 1 Preparing the holes for anchoring

Fig. 2 Preparing the new stone

Fig. 3 Fixing the new stone

Fig. 1 anchoring the stone
RECONSTRUCTION OF CORNICE WITH MORTAR

Fig. 1 Injection process

Fig. 2 Reconstruction process

Fig. 3 Cornice fragment after reconstruction
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27.09.2001
# RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

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**Part III – GLOSSARY**

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PURPOSE OF THE DOCUMENT

Structures of architectural heritage, by their very nature (material and assembly), present a number of specific challenges in diagnosis and restoration that limit the application of modern legal codes and building standards. Recommendations are not only desirable but necessary in order to place relevant procedures within a rational scientific setting and within a cultural context.

The Recommendations presented in this document are made of three parts: Principles, where the basic concepts of conservation are presented; Guidelines, where the rules and methodology that a designer should follow are discussed; Glossary where the meaning of the terms more frequently used are clarified.

These Recommendations are intended to be useful to all those involved in conservation and restoration problems, but can’t in anyway replace specific knowledge acquired in cultural and scientific books.
Part I

PRINCIPLES

1 General criteria

1.1 Conservation, reinforcement and restoration of architectural heritage requires a multidisciplinary approach.

1.2 Value and authenticity of architectural heritage cannot be based on fixed criteria because the respect due to all cultures also requires that its physical heritage be considered within the cultural context to which it belongs.

1.3 The value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time. In particular the removal of the inner structures maintaining only the façades does not fit the conservation criteria.

1.4 When any change of use or function is proposed, all the conservation requirements and safety conditions have to be carefully taken into account.

1.5 Restoration of the structure in Architecture Heritage is not an end in itself but a means to an end which is the building as a whole.

1.6 The peculiarity of heritage structures, with their complex history, requires the organisation of studies and proposals in precise steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the searches for significant data and information, individuation of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions. In order to achieve cost effectiveness and minimal impact on architectural heritage using funds available in a rational way, it is usually necessary that the study repeats these steps in an iterative process.

1.7 No action should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage, except in cases where urgent safeguard measures are necessary to avoid the imminent collapse of the structures (e.g. after seismic damages); those urgent measures, however, should when possible avoid modifying the fabric in an irreversible way.
2 Researches and diagnosis

2.1 Usually a multidisciplinary team, to be determined in relation to the type and the scale of the problem, should work together from the first steps of a study - as in the initial survey of the site and the preparation of the investigation programme.

2.2 Data and information should first be processed approximately, to establish a more comprehensive plan of activities in proportion to the real problems of the structures.

2.3 A full understanding of the structural and material characteristics is required in conservation practice. Information is essential on the structure in its original and earlier states, on the techniques that were used in the construction, on the alterations and their effects, on the phenomena that have occurred, and, finally, on its present state.

2.4 In archaeological sites specific problems may be posed because structures have to be stabilised during excavation when knowledge is not yet complete. The structural responses to a “rediscovered” building may be completely different from those to an “exposed” building. Urgent site-structural-solutions, required to stabilise the structure as it is being excavated, should not compromise the complete building’s concept form and use.

2.5 Diagnosis is based on historical, qualitative and quantitative approaches; the qualitative approach being mainly based on direct observation of the structural damage and material decay as well as historical and archaeological research, and the quantitative approach mainly on material and structural tests, monitoring and structural analysis.

2.6 Before making a decision on structural intervention it is indispensable to determine first the causes of damage and decay, and then to evaluate the safety level of the structure.

2.7 The safety evaluation, which is the last step in the diagnosis, where the need for treatment measures is determined, should reconcile qualitative with quantitative analysis: direct observation, historical research, structural analysis and, if it is the case, experiments and tests.

2.8 Often the application of the same safety levels as in the design of new buildings requires excessive, if not impossible, measures. In these cases specific analyses and appropriate considerations may justify different approaches to safety.

2.9 All aspects related to the acquired information, the diagnosis including the safety evaluation, and the decision to intervene should be described in an “EXPLANATORY REPORT”.

27.09.2001
3 Remedial measures and controls

3.1 Therapy should address root causes rather than symptoms.
3.2 The best therapy is preventive maintenance.
3.3 Safety evaluation and an understanding of the significance of the structure should be the basis for conservation and reinforcement measures.
3.4 No actions should be undertaken without demonstrating that they are indispensable.
3.5 Each intervention should be in proportion to the safety objectives set, thus keeping intervention to the minimum to guarantee safety and durability with the least harm to heritage values.
3.6 The design of intervention should be based on a clear understanding of the kinds of actions that were the cause of the damage and decay as well as those that are taken into account for the analysis of the structure after intervention; because the design will be dependent upon them.
3.7 The choice between “traditional” and “innovative” techniques should be weighed up on a case-by-case basis and preference given to those that are least invasive and most compatible with heritage values, bearing in mind safety and durability requirements.
3.8 At times the difficulty of evaluating the real safety levels and the possible benefits of interventions may suggest “an observational method”, i.e. an incremental approach, starting from a minimum level of intervention, with the possible subsequent adoption of a series of supplementary or corrective measures.
3.9 Where possible, any measures adopted should be “reversible” so that they can be removed and replaced with more suitable measures when new knowledge is acquired. Where they are not completely reversible, interventions should not limit further interventions.
3.10 The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term impacts, so that undesirable side-effects are avoided.
3.11 The distinguishing qualities of the structure and its environment, in their original or earlier states, should not be destroyed.
3.12 Each intervention should, as far as possible, respect the concept, techniques and historical value of the original or earlier states of the structure and leaves evidence that can be recognised in the future.
3.13 Intervention should be the result of an overall integrated plan that gives due weight to the different aspects of architecture, structure, installations and functionality.
3.14 The removal or alteration of any historic material or distinctive architectural features should be avoided whenever possible.

3.15 Deteriorated structures whenever possible should be repaired rather than replaced.

3.16 Imperfections and alterations, when they have become part of the history of the structure, should be maintained so far so they do not compromise the safety requirements.

3.17 Dismantling and reassembly should only be undertaken as an optional measure required by the very nature of the materials and structure when conservation by other means impossible, or harmful.

3.18 Provisional safeguard systems used during the intervention should show their purpose and function without creating any harm to heritage values.

3.19 Any proposal for intervention must be accompanied by a programme of control to be carried out, as far as possible, while the work is in progress.

3.20 Measures that are impossible to control during execution should not be allowed.

3.21 Checks and monitoring during and after the intervention should be carried out to ascertain the efficacy of the results.

3.22 All the activities of checking and monitoring should be documented and kept as part of the history of the structure.
1 General criteria
A combination of scientific and cultural knowledge and experience is indispensable for the correct approach to the study of all architectural heritage. Failure to recognize this may lead to the false assumption that any problem can be solved through the application of these guidelines alone. Only when science and culture are combined can the guidelines help to better conservation, strengthening and restoration of buildings, bearing in mind that the purpose of both research and intervention is to safeguard the cultural and historical value of the building as a whole and that structural engineering is part of the scientific support necessary to obtain this result. The conservation of architectural heritage usually requires a multidisciplinary approach involving a variety of professionals and organisations. These guidelines have been prepared to assist this work and facilitate communication between those involved.

Any study or planning for structural conservation calls for both qualitative data, based on the direct observation of material decay, structural damage, historical research etc., as well as quantitative data based on specific tests and mathematical models of the kind used in modern engineering. This combination of approaches makes it very difficult to establish rules and codes. While a lack of clear guidelines can easily result in ambiguities and arbitrary decisions, codes that are not prepared explicitly for historic structures are often inappropriately applied. Examples are the use of seismic and geotechnical codes, whose enforcement can lead to drastic and often unnecessary measures that fail to take account of real structural behaviour.

The subjective aspects involved in the study and safety assessment of an historic building, uncertainties in the data assumed and difficulties in making a precise evaluation of the phenomena, may lead to conclusions of uncertain reliability. It is important, therefore, to present all these aspects clearly, and in particular demonstrate both the care taken in the development of the study and the reliability of the results, in an EXPLANATORY REPORT. This will facilitate the final judgement on the safety of the structure and the decisions to be taken.
The evaluation of a building normally requires a holistic approach, proceeding from the general to the particular, i.e. from an assessment of the behaviour of the overall structure, to an assessment of individual members and material properties.

2 Acquisition of data: Information and Investigation

2.1 Generally

The investigation of a structure requires an interdisciplinary approach. For example, the direction of historical research may sometimes be directed by questions of structural significance, while the historian may have questions which require structural information. Therefore it is important that a team of investigators be formed including a range of skills appropriate to the characteristic of the building, and directed by someone with adequate experience.

Knowledge of the structure requires information on its conception, on the techniques used in its construction, on subsequent processes and events that have affected it and finally on its present state. This knowledge can usually be reached by the following steps:

- historical research covering the entire life of the structure;
- definition, description and understanding of its historic and cultural significance, and of the original building materials and techniques;
- description of the structure in its present state including identification of damage, decay and possible progressive phenomena, using appropriate types of test;
- identification of the forces involved, the structural behaviour and types of materials;
- an account of any previous interventions;

A pre-survey of both the site and the building should orient these studies. Because these can all be carried out at different levels of detail it is important to establish a cost effective plan of activities that are proportional to the problems of the structure and, if necessary, to be carried out in several stages.

2.2 Historical, structural and architectural investigations

The aim of the historical survey is to understand the design, conception and significance of the building, the techniques and the workmanship used in its construction, the changes in both the structure and its environment and finally the events that may have caused damage. Careful attention should be paid to the methods of recording the documents collected. Meticulous validation and interpretation are essential if the data so acquired are to produce reliable information about the structural history of a building.
Once all the documentation has been assembled, the sources should be graded according to their reliability as part of any attempt to produce a history of the construction. Assumptions made in the interpretation of historical material should be made clear. Particular attention should be paid to any damage, failures, reconstructions, additions, unauthorised changes, restoration work, structural modifications, and any changes in the use of the structure that have led to its present condition. It should be remembered that documents which may be used in this process were usually prepared for purposes different from structural engineering and may therefore include technical information which is either incorrect or may omit or misrepresent key facts or events which are important from a structural point of view.

2.3 Survey of the structure

Direct observation of the structure is an essential phase of the study, usually carried out by a qualified team to provide an initial understanding of the structure and to give an appropriate direction to the subsequent investigations.

Among the main objectives are:
I) to identify decay and damage,
II) to determine whether the phenomena have stabilised or not,
III) to decide if there are immediate risks and urgent measures to be undertaken,
IV) to discover if the environment is damaging the building.

The study of structural faults begins by mapping visible damage and is a task requiring care and skill in which interpretation of the findings should be used to guide the survey process. During this process the expert should already be developing an idea of possible structural schemes so that critical aspects of the structure may be examined in more detail.

Geometrical surveys should map different kinds of materials, noting any decay, structural irregularities and damage, paying particular attention to the crack patterns and evidence of crushing. Geometric irregularities can be the result of previous deformations and can indicate the junction between different building phases or alterations to the fabric.

It is important to discover how the environment may be damaging a building, because this is exacerbated by lack of proper care during construction (drainage, condensation, rising damp due to capillary action, etc.), the use of unsuitable materials and by poor subsequent maintenance. Observation of areas where damage is concentrated, and in particular "zones of
crushing” (high compression) and “zones of cracks or detachments” (high tensions), including the analysis of their directions, together with an investigation of soil conditions, may indicate the causes of such damage. This may be supplemented by information obtained by specific tests and often involves an iterative process, where the results of tests suggest the need for further investigations.

2.4 Field research and laboratory testing
The schedule of tests should be based on a clear view of the phenomena whose understanding could be relevant. Tests usually aim to identify the mechanical (strength, deformability, etc.), physical (porosity, etc.) and chemical (composition, etc.) characteristics of the materials, the stresses and deformations of the structure, the presence of discontinuities and cracks inside the structure, etc. As a rule, the schedule of tests should be divided into stages, starting with the acquisition of basic data, with subsequent work based upon an assessment of the implications of this initial data. Non-destructive tests should be preferred to those that involve either major or minor alterations to a structure. If the former are insufficient, a “cost-benefit” analysis of any proposed alterations should be carried out balancing any cultural losses that might be incurred to improve knowledge against the value of the knowledge that might be obtained and which might enable reduced structural interventions.

Tests should always be carried out by skilled persons able to gauge their reliability correctly and the implications of test data should be very carefully assessed. If possible different methods should be used and the results compared. It may also be necessary to carry out tests on selected samples taken from the structure.

2.5 Long term monitoring
Structural observation over a period of time may be necessary, not only to acquire information when progressive phenomena is suspected, but also during the different stages of structural renovation. During the latter, monitoring the effects of each stage (observational approach) can provide data to be used for future decision making. Monitoring systems usually aim to record changes in deformations such as crack widths. Such monitoring can also act as an alarm bell. Dynamic monitoring is used to record accelerations, such as those in seismic areas.

The simplest and cheapest way to monitor change in crack widths is to place a “tell-tale” across them. Some cases might require the use of computerised monitoring systems in which
various devices are connected to a computer, which records all the data at intervals of time. As a general rule, the use of a monitoring system should be subjected to cost-benefit analysis and only data that are strictly necessary to reveal progressive phenomena should be gathered.

3 The structural behaviour

3.1 General aspects

The behaviour of any structure is influenced by three main factors: the shape and the connections of the structure, the construction materials and the actions. These factors are here examined in detail.

3.2 The structural scheme and damage

Structural behaviour depends on the characteristics of the materials used, the dimensions of the structure, the connections between different elements, the soil conditions, etc. The real behaviour of a building is usually so complex that we are obliged to represent it with a simplified 'structural scheme'; that is with an idealisation of the building which shows, in a more or less precise way, its function in resisting the various actions. The structural scheme shows the way the building transforms actions into stresses and ensures stability.

A building may be represented by different schemes with different complexity and different degrees of approximation to reality. The original structural scheme may change due to damage, reinforcement, or other modifications of the building. The scheme assumed for the calculations has to take into account any alterations and weakening, such as cracks, discontinuities, crushing, leanings, etc., whose effect may significantly influence the structural behaviour. These alterations may be produced either by natural phenomena or by human interventions. The latter may include:

- the reduction of the bearing capacity due to the making of openings, niches, etc.;
- the creation of unbalanced forces due to the elimination of arches, slabs, walls, etc.;
- the increase of the weight as a result of adding heights to the structure;
- the reduction of the soil capacity due to excavations, galleries, nearby buildings, etc.).

3.2 The material characteristics and decay processes

Material properties (particularly strength), which are the basic parameters for any calculation, may be reduced by decay processes because of chemical, physical or biological
action. The rate of decay depends upon the properties of the materials (such as porosity), the way the structure is protected (roof overhangs, etc.) as well as its maintenance. Although decay may manifest itself on the surface, and so be immediately apparent from superficial inspection (such as efflorescence or increased porosity), there are also decay processes which can only be detected by more sophisticated tests (such as termite attack in timber).

3.3 The actions on the structure and the materials

'Actions' are defined as any agent (forces, deformations, etc.) that produce stresses and strains in the structure and any phenomenon (chemical, biological, etc.) that affects the materials, usually reducing their strength. The original actions, which occur from the beginning of the construction to completion of the building (dead loads, for example), may be modified during its life and it is often these changes which produce damage and decay. Actions have very different natures with very different effects on the structure and on the materials. Often more than one action (or, perhaps unexpected modification of the original actions), will have affected the structure and these actions must clearly be identified before deciding the repair measures.

Actions may be classified as follows:

I) Mechanical actions. These, which are either static or dynamic, as described below, may be the cause of different kinds of damage (cracks, deformations, etc.).

I.1) Static actions. These can be of two kinds

I.1.1) Direct actions (i.e. applied forces). These consist of applied loads such as dead loads (weight of the building, etc.) and live loads (furniture, people, etc.). Changes in load conditions, mainly increases, are sources of increased stresses and thus of damage in the structure. In some cases decreases in load conditions can also be source of damage to the structure.

I.1.2) Indirect actions (imposed deformations). These consist of deformations, such as soil settlements, imposed on the boundaries of the structure or produced within the body of the materials, such as thermal movements, creep in timber, shrinkage in mortar, etc. These actions, which may vary continuously or cyclically, produce forces only if deformations and strains are not free to develop. The most important and often most dangerous of all indirect actions are soil settlements (produced by changes in the water table, excavations, etc.) and may create large cracks, leaning, etc.
A number of indirect actions are cyclic in nature, including temperature changes and some ground movements due to seasonal variation in ground water levels. While the effects produced may also be cyclic it is also possible for progressive deformation to be produced by such cyclic effects where each cycle produces some small but permanent change within the structure.

The temperature gradient between outer surfaces and the internal body may be the cause of differential strains in the material and therefore of stresses and micro-cracks, which further accelerate the decay.

The progressive reduction of the stiffness of the elements of an hyperstatic structure (weakening, decay processes, etc.), can also be regarded as an indirect action when this results in a redistribution of stresses.

I.2) Dynamic actions. These are produced when accelerations are transmitted to a structure, as a result of earthquakes, wind, hurricanes, vibrating machinery, etc. The most significant dynamic action is usually caused by earthquakes. The intensity of the forces produced is related to both the intensity of the acceleration and also to the natural frequencies of the structure and its capacity to dissipate energy. The effect of an earthquake is not only a function of the forces generated but is also related to the history of previous earthquakes that may have progressively weakened the structure.

II) Physical, chemical, and biological actions. These actions are of completely different nature from those previously described. They may produce different kinds of decay and consequently change the properties of the materials and so their strength.

Material properties may change over time due to natural processes characteristic of each material, such as the slow hardening of lime mortar or slow internal decay. These actions may be influenced and exacerbated by the presence of water (rain, humidity, ground water, wetting and drying cycles, organic growth, etc.), variations in temperature (expansion and contraction, frost action, etc.) and micro-climatic conditions (pollution, surface deposition, changes in wind speeds due to adjacent structures, etc.). Fire can be considered as an extreme change of temperature.
A very common action is the oxidation of metals, which may either be visible on the surface or may be occurring to metal reinforcing placed inside a material and therefore only apparent through secondary effects, such as splitting and spalling of the material.

Chemical changes may occur spontaneously because of the inherent characteristics of the material or be produced as a result of external agents, such as the deposition of pollutants, or the migration of water or other agents through the material.

**Biological agents are often active in areas which are not easily inspected and it is necessary** to be aware of this and take appropriate measures.

Identifying the mechanism by which the change is occurring must be part of the diagnostic process.

4 Diagnosis and safety evaluation

4.1 General aspects

Diagnosis and safety evaluation of the structure are two consecutive and related stages on the basis of which the effective need for and extent of treatment measures are determined. If these stages are performed incorrectly, the resulting decisions will be arbitrary and frequently excessive: poor judgement will result in either heavy-handed conservation measures or inadequate safety levels.

Evaluation of the safety of the building should be based on both qualitative (in the form of documentation, observation, etc.) and quantitative (in the form of experimental, mathematical, etc.) methods that take into account the interaction of both the phenomena involved and the structural behaviour.

Any assessment of safety is seriously affected by two types of problem:

- the uncertainty attached to the data (actions, resistance, deformations, etc.), laws, models, assumptions, etc. used in the research;
- the difficulty of representing real phenomena in a precise way.

It therefore, seems reasonable to adopt different approaches, each of which can provide a separate contribution, but which combine to produce the best "verdict" possible based on the knowledge and individual skills available. When making a safety assessment, it is also necessary to include some indication, even if only qualitative, of the reliability of the data.
obtained and the degree of caution embodied in the assumptions made and the measures proposed.

Modern legal codes and professional codes of practice adopt a conservative approach involving the application of safety factors to take into account the various uncertainties. This is appropriate in new structures where safety can be increased with modest increases in member size and cost. However, such an approach is not appropriate in historic structures where requirements to improve reserves of strength may lead to the loss of historic fabric or historic character and may add cost. A more flexible and broader approach needs to be adopted for historic structures to relate the remedial measures more closely to the actual safety requirements and to keep the principle of minimum intervention.

The verdict on a structure's safety is based on an evaluation of the results obtained from the three diagnostic procedures that will be discussed below, bearing in mind that the qualitative approach plays a role as important as the quantitative approach. It also has to be noted that the safety factors established for new buildings take into account several uncertainties related to construction. In existing buildings these uncertainties may be reduced because the real behaviour of the structure can be observed and monitored. Therefore, if data are more reliable, reduced theoretical factors of safety do not necessarily correspond to a real reduced safety. (However see also 4.3.1 & 4.3.4 III below)

4.2 Identification of the causes (Diagnosis)
The diagnosis identifies the causes of damage and decay, on the basis of the acquired data, following three headings:
- Historical analysis (documents, etc.)
- Qualitative analysis (survey, investigation, etc.)
- Quantitative analysis (test, mathematical models, etc.)

Diagnosis is often a difficult phase, since the data available usually refer to effects, while it is the cause - or, as more often is the case, the several concomitant causes – that have to be determined. This is why intuition and experience are essential components in the diagnostic process. A correct diagnosis is indispensable for a proper evaluation of safety and for rational decisions on the treatment measures to be adopted.

4.3 Safety evaluation
4.3.1 The problem of safety evaluation
Safety evaluation is the next step towards completion of the diagnosis phase.

Whilst the object of diagnosis is to identify the causes of damage and decay, a safety evaluation must determine whether or not the safety levels are acceptable by analysing the present condition of both structure and materials. The safety evaluation is therefore an essential step in the process of restoration because this is where decisions are taken of the need for and extent of any remedial measures.

However, safety evaluation is also a difficult task because methods of structural analysis used as the basis for new construction may be neither accurate nor reliable for historic structures and may result in inappropriate decisions. This is due to several factors, such as difficulty in properly understanding the complexity of an ancient building or monument, uncertainties regarding material characteristics, the unknown influence of previous phenomena (for example soil settlements), and imperfect knowledge of alterations and repairs carried out in the past, etc.

Therefore, a quantitative approach based on mathematical models cannot be the only procedure to be followed. As with the diagnosis qualitative approaches based on the historical research and on observation of the structure, should also be followed. A fourth approach based on specific tests may be useful in some situations.

Each of these approaches, which are listed below, can inform the safety evaluation, but it is the combined analysis of the information obtained from them which may lead to the 'best judgement'. In forming this judgement both objective and subjective aspects should be taken into account having been weighed on the basis of the reliability of the data and assumptions made. All this should be part of the "EXPLANATORY REPORT" already discussed.

It must be clear, therefore, that the architect or engineer charged with the safety evaluation of an historic building should not be legally obliged to base his decisions solely on the results of calculations, because structural analysis may be inappropriate for certain specific problems.

Similar procedures have to be followed to evaluate the safety levels after the design of some kinds of intervention (see para. 5) or reinforcement in order to evaluate their benefits and to ensure that their adoption is appropriate (neither insufficient nor excessive).
4.3.2 (I) The historical approach

Knowledge of what has occurred in the past can help to forecast future behaviour and is a useful basis on which to estimate the level of safety provided by the present state of the structure. History is the most complete, life-size, experimental laboratory imaginable. It demonstrates how the type of structure, the building materials, connections, joints, additions and human alterations have interacted with natural events, such as overloads, earthquakes, landslides, temperature variations, atmospheric pollution, etc., perhaps altering the structure’s original behaviour by causing cracks, fissures, crushing, movement out-of-plumb, decay, collapse, etc. The structural task is to discard superfluous information and correctly interpret the data relevant to describing the static and dynamic behaviour of the structure.

Although satisfactory behaviour shown in the past is an important factor for predicting the future survival of the building, one needs to be aware that past stability is not always a reliable guide to future safety. This is particularly true where the structure is working at the limit of its bearing capacity and brittle behaviour is involved (such as high compression in columns), when there are significant changes in the structure or when repeated actions are possible (such as earthquakes) that progressively weaken the structure.

4.3.3 (II) The qualitative approach

A comparison can often be made between the present condition of structure and that of other similar structures whose behaviour has already been understood. The experience gained from analysing and comparing the behaviour of different structures can enhance the usefulness of extrapolations and can offer a reliable basis for an evaluation of safety. However, this approach, known in philosophical terms as an inductive procedure, is not entirely reliable because such evaluation depends more upon personal judgement than on strictly scientific procedures. Nonetheless, it may prove the most rational approach. Because of uncertainties inherent in the problems involved other approaches only often only give the appearance of being more rigorous and reliable.

Having observed the behaviour of different structural types of buildings in varying stages of damage and decay caused by different actions (earthquakes, soil settlement, etc.), and having acquired an experience of their soundness and durability, it is possible to extrapolate this knowledge to predicting the behaviour of the particular structure under examination. Obviously, the reliability of any such evaluation will depend on the number of structures.
observed and therefore on the experience and judgement of the individuals concerned, as well as on their perspicacity, but appropriate investigation and monitoring of progressive phenomena may increase the reliability of this evaluation.

4.3.4 (III) The analytic approach

This approach is based on the methods of the modern structural analysis which, on the basis of certain hypotheses, (theory of elasticity, theory of plasticity, frame models, etc.) draws conclusions by applying strictly logical deduction based on mathematical calculations. In philosophical terms it belongs to the deductive procedure. However, the uncertainties that can affect the simplified representation of a materials’ behaviour, and the imperfect representation of the structural behaviour, together with the fact that the theories and simplifications adopted are not always completely reliable, can give misleading results which may be very different from the real situation. The essence of the problem is thus the identification of meaningful models that adequately depict both the structure and the associated phenomena with all their complexity, making it possible to apply the theories at our disposal.

Mathematical models are the common tools used in structural analysis; models describing the original structure, if appropriately calibrated, allow comparison of the theoretical damage produced by different kinds of actions with the damage actually surveyed, providing a useful tool for identifying the causes of such damage. Mathematical models of the damaged and then of the reinforced structure, will help to evaluate the present safety levels and to assess the benefits of proposed measures.

Structural analysis is an indispensable tool. Even when the result of calculations and analysis cannot be precise, they can indicate trends in stresses, possible critical areas, the flow of the stresses and so on. However, mathematical models alone cannot satisfy the legal requirement for an appropriate analysis of the structure. Grasping the key issues and correctly setting the limits for the use of mathematical techniques depends upon the expert's use of his scientific knowledge. Any mathematical model must take into account the three aspects described in para. 3: i.e. the structural scheme, the material characteristics and the actions to which the structure is subjected.

4.3.5 (IV) The experimental approach
Specific tests may facilitate evaluation of the safety margins, even if they are applicable only to single structural elements or materials (such as loading a floor, a beam, etc.) and not to the building as a whole. The analysis of the results contributes to the evaluation of safety margins.

4.4 Decisions and explanatory report

The judgement on a structure's safety is based on the results of the three (or four) main approaches described above (the fourth approach having limited application). When a method of analysis indicates inadequate safety levels, it should be checked to see if the analysis has used either insufficiently accurate data or values that are excessively conservative. This may lead to the conclusion that more investigation is necessary before a diagnosis can be made. Because qualitative judgements may play a role as important as quantitative data, the safety assessment and the consequent decisions on intervention should be set down in the EXPLANATORY REPORT (already referred to) where all the considerations which have led to the final evaluation and the decisions are clearly explained. The verdict must take into account both the degree of accuracy and of caution underlying each decision and must be based on logically consistent reasoning.

Time factors must be considered in the “Explanatory report”, because a decision to undertake immediate measures, or a decision to accept the status quo, are simply two extremes in a scale of choices. The alternatives are often to strengthening the structure on the basis of present knowledge or to extend research to obtain more complete and reliable data in the hope of reducing any intervention. However some deadline must be set for implementing the decisions, bearing in mind that safety is of probabilistic nature with the likelihood of failure increasing the longer remedial action is delayed.

The factors underlying the setting of a deadline will depend essentially on three types of phenomena:

• continuous processes that will eventually reduce safety levels to below acceptable limits, so that adequate measures must be taken before that occurs (as for example decay process, slow soil settlements, etc.);

• phenomena of cyclical nature (variation in temperature, moisture content, etc.) that will produce increasing deterioration;

• phenomena that can suddenly occur, such as earthquakes, hurricanes, etc. The probability of these occurring at any defined level increases with the passage of time, so that the degree of
safety to be provided can theoretically be linked to the life expectancy of the structure (for example, it is well known that if it is desired to protect a building against earthquakes for five centuries it is necessary to assume greater accelerations than those assumed to protect the same building for one century).

5 Structural damage, materials decay and remedial measures

5.1 General aspects

This section considers decision processes involved in both the investigation of a structure and the selection of remedial measures to be applied. In the following paragraphs some examples of the most frequent damage and repair criteria for the main structural elements are outlined, without pretending to provide an exhaustive picture of the many possible solutions published elsewhere.

Structural damage occurs when the stresses produced by one or more action (see 3.3.4, c) exceed the strength of the materials in significant zones, either as because the actions themselves have increased or because strength has been reduced (see 3.3.4, b). Substantial changes in the structure, including partial demolition, (see 3.3.4, a) may also be a source of damage.

Manifestation of damage is related to the kind of actions and the construction materials. Brittle materials will fail with low deformations while ductile materials will exhibit considerable deformation before failure.

The appearance of damage, and in particular cracks, is not necessarily an indication of a risk of failure in a structure because cracks may relieve stresses that are not essential for equilibrium (as for example certain kind of cracks produced by soil settlements) and may, through changes in the structural system, allow a beneficial redistribution of stresses. However, immediate measures are required when damage produces irreversible alterations to historic buildings or when safety levels are compromised.

Damage may also occur in non-structural elements, e.g. cladding or internal partitions, as a result of stresses developed within those elements due to movement or dimensional changes within the structure.
Sometimes a structure does not consist of a single material; for example, steel or concrete frames may be infilled with brick masonry that may have an important stiffening function. Masonry walls may be reinforced with metal or timber or may incorporate framed openings which act differently from the remainder of the masonry and so affect the overall behaviour. It is important to consider the relative behaviour of these different materials under load, both in the short and longer term, and their different weathering or decay characteristics.

Material decay brought about by chemical, physical and biological actions and may be exacerbated when these actions are modified in an unfavourable way (for example pollution, etc.). The main consequences are deterioration of surfaces, loss of material and, from the mechanical point of view, a reduction of strength. Retention of material characteristics is therefore an important task for the conservation of historic buildings and maintenance is the best way to achieve this goal. This is particularly important because while 'preventing' decay is usually possible, 'repair' is often much more difficult and uncertain.

5.2 Masonry building

5.2.1 Generally

The term masonry here refers to stone, brick and earth based construction (i.e. adobe, pisé de terre, cobb, etc.). Masonry and adobe structures are generally made of materials that have a very low tensile strength, and may show cracking within, or separation between elements. Nevertheless, these signs are not necessarily an indication of danger as masonry structures are intended to work only (or mainly) in compression.

The preliminary diagnosis of masonry should determine the characteristics of the constituent s of this as composite material (the stones or bricks: limestone, sandstone, fired or sun dried etc., and the type of mortar: cement, lime, etc.) upon which its overall properties depend. It is also necessary to know how the elements are bonded (dry joints, mortar joints, etc.) and the way in which they are geometrically related to each other. Different kind of tests may be used to ascertain the composition of the wall (endoscopic tests, etc.).

Masonry structures commonly rely upon the effect of the floors or roofs that they support to distribute lateral loads and so ensure the overall stability of the structure. The disposition of such structures and their effective connection to the masonry needs to be considered.
Where buildings have been altered, differences in the behaviour of the different periods of masonry may produce signs of distress.

### 5.2.2 Walls, columns and piers

Vertical loads are the main cause of damage or collapse of the masonry (crushing, buckling, brittle failure, etc.). These situations are particularly dangerous because they usually happen with small deformations and few visible signs. Lateral forces and their effects are relevant in seismic areas, in tall constructions, and where there is the thrust of arches or vaults.

Particularly attention has to be paid to large walls whose construction may comprise different kinds of material. Such walls include cavity walls, rubble filled masonry walls and veneered brick walls which have a poor quality core. Not only may the interior of the wall be less capable of carrying load but movement of the core material may also be a source of new stresses. In this type of masonry the external leaves can separate from the internal core so that consideration needs to be given to whether the facing material and the fill are acting together or separately. The latter is potentially dangerous because the faces may become unstable. Moreover disturbance of the core can result in lateral loads on the facings which may be a progressive phenomenon. It is therefore important to assess the load path within the wall.

To understand the cause of damage (diagnosis) it is first necessary to evaluate levels and distribution of stress, even if approximately, because they are usually very low and, even if there are some errors in the evaluation, that does not significantly affect the safety margin. A visual inspection (for example taking into account the crack pattern) may provide an indication of load paths within a structure.

When there is the risk that the stresses in significant areas would be too close to the ultimate strength of the masonry it is necessary either to carry out a more accurate structural analysis or specific tests on the masonry (flat jack test, sonic test, etc.) to provide a more accurate assessment of the strength.

Compressive stresses close to the capacity of the materials can cause vertical cracks as the first sign of damage eventually leading to large lateral deformations, spalling, etc. The extent to which these effects become visible depends upon the material’s characteristics and in particular its brittleness. They can develop either very slowly (even over centuries) or quickly, but stresses close to the ultimate strength will result in collapse even if the loads remain constant.
In-plane lateral loads can cause diagonal cracks or sliding. Out-of-plane or eccentric loads may cause separation of the leaves in a multi-leaf wall or rotation of an entire wall about its base. Where the latter occurs, horizontal cracks at the base will be seen before overturning occurs.

Intervention may be divided into:

i) Repointing of the existing masonry
ii) Consolidation of the existing wall with grout.
iii) Reinforcing the wall with either vertical, longitudinal or transverse reinforcement.
iv) Removal and replacement of decayed material.
v) Dismantling and rebuilding, either partially or completely.

While interventions to address problems of both extensive cracking and decay are often carried out by the injection of appropriate fluid mortars to consolidate the masonry (grouting), the selection of these (lime, cement, resins, special products, etc.) depends on the characteristics of the masonry. Particular attention has to be given to the compatibility between original and new materials.

The use of cement-containing mortars should be avoided in the restoration of a historic building. In walls built with gypsum-containing mortars, the reaction between gypsum and cement-minerals results in the formation of salts that sooner or later will lead to destruction. In other cases there may be a problem of leaching of soluble salts from the mortar resulting in efflorescence on the surface of brickwork, (particularly dangerous when there are historic plasters or frescoes) or there may be changes in the path of moisture through the wall.

Apart from the consolidation of the material itself (by grouting when possible or by repointing) the most efficient measures to counter both the effect of vertical loads and internal pressures in rubble core walls are the use of ties made of appropriate materials.

A number of different products are available for protection or consolidation of surfaces that have no plaster to protect them. However, these are seldom completely effective and particular attention has to be paid to possible side effects.

Finally it has to be noticed that introducing other materials into the masonry may locally modify its stiffness; and the possible significance of this alteration has to be taken into account. As a rule the use of reinforced concrete to strengthen masonry buildings should be avoided.
5.2.3 Arches and vaults

Arches and vaults are structures relying on thrust at the springers to reduce or eliminate bending moments, thus allowing the use of materials with low tensile strength or construction without mortar (dry stone blocks, etc.). Their load bearing capacity is excellent and it is the movement of the springers, thus introducing bending moments and tensile stresses, that usually leads to opening of the joints and eventual collapse.

The formation of thin cracks is quite normal to the behaviour of some vaulted structures. In others inadequate behaviour is often associated with poor execution, (poor bonding of units, low material quality, etc.), inappropriate geometry for the load distribution, or inadequate strength and stiffness of those components that must take the thrusts (chains, abutments).

When the construction material has very low strength (as in structures made of irregular stones with a lot of mortar) it is possible to have the detachment of portions of the vaults, possibly leading to progressive collapse, in those zones where the compression is lower or where there are tension stresses.

Due consideration is to be paid to the relationship between load distribution and the geometry of the structure when loads (especially heavy dead loads) are removed or added to vaulted masonry structures.

The main repair measures that can be used derive from due consideration of the above points, i.e.:

- Substitution of existing and in some cases addition of new tie rods (usually at the spring level in the vaults, or along parallel circles in the domes);
- Construction of buttresses;
- Correction of the load distribution (in some cases loads should be added);
- In the most critical case, re-construction of parts of masonry, repointing of mortar joints and consolidation of the masonry.

5.2.4 Towers

High rise buildings such as towers, bell towers, minarets, etc., are characterised by high compression stresses and present problems similar to those of pillars and columns. In addition, these structures are further weakened by imperfect connections between the walls, by alterations such as the making or closing of openings, etc. When correctly positioned,
horizontal tie bars and chains, and sometimes diaphragms, can improve their ability to resist gravity loads.
These structures are easily damaged by earthquakes.

5.3 Timber
Wood has been used in a wide variety of structural forms. It is used as the basic structural material in both load-bearing and framed structures, in composite structures of wood and masonry and to form major elements of load-bearing masonry structures. Its structural performance is affected by species, growth characteristics, changes that take place in the processes between felling and use and by decay in use. Preliminary operations should be the identification of the species, which are differently susceptible to biological attack, and the evaluation of the strength of individual members. This can often be based on a visual examination of the structure (the number and distribution of knots and other growth characteristics).

Durability may also be affected by the methods of harvesting, seasoning and conversion, which may have been quite different in different times. Longitudinal cracks parallel to the fibres due to drying shrinkage are not dangerous when their dimension are small. Fungal and insect attack are the main source of damage. These are linked to a high moisture content and temperature.

Contact with masonry is often a source of moisture. This may occur either where the masonry supports the timber or where timber has been used to reinforce the masonry. However, poor maintenance of buildings or radical changes in the internal conditions are the most common causes of timber decay.

Because decay and insect attack may not be visible at the surface, methods, such as micro-drilling, are available for the examination of the interior of the timber. The in-service moisture content should also be measured as an indication of vulnerability to attack. Chemical products can protect the wood against biological attack. For example, in floors or roofs the ends of the beams inserted into masonry walls are susceptible to decay as result of moisture and should be protected.

Where either reinforcing materials or consolidants are introduced, their compatibility with the timber structure must be verified. For example steel fasteners may be susceptible to corrosion...
in association with some species and so stainless steels should be used. Interventions should not hinder the breathing of the timber to the environment.

To dismantle and reassemble timber structures is a delicate operation because of the risk of damage. There is also the possible loss of heritage value in the loss of associated materials. Because many timber structures were originally prefabricated, there are circumstances where either partial or complete dismantling may facilitate an effective repair.

Timber is often used to form framed and trussed structures where the main problems are often related to local failure at the nodes. Common remedial measures consist in reinforcing the nodes or adding supplementary diagonal elements, when it is necessary, to improve the stability against lateral forces.

5.4 Iron and steel

It is necessary to distinguish between cast iron, wrought iron and steel structures. The first is not only weak in tension but may contain built in stresses resulting from the casting process. Iron and steel used in construction are alloys and their susceptibility to corrosion depends upon their composition. Note that corrosion is always accompanied by an increase in the volume of material that may give rise to stresses in associated materials; for example the splitting of stone or concrete as a result of the corrosion of inserted iron bars or cramps.

The most vulnerable aspects of steel structures are their connections where stresses are generally highest, especially at holes for fasteners. Bridges or other structures subjected to repeated loading might be subject to fatigue failure. Therefore in riveted and bolted connections it is very important to check cracks starting from the holes. Fracture analysis enables the remaining life-span of the structure to be assessed.

Protection against corrosion of iron and steel requires first the elimination of rust from the surfaces (by sand blasting, etc.) and then painting the surface with an appropriate product. Heavily damaged and deformed iron or steel structures usually cannot be repaired. Strengthening of weak structures can often be achieved adding new elements, paying particular attention when welding.
5.5 Reinforced concrete

Reinforced and prestressed concrete are the basic materials of many modern buildings that are now recognised as being of historic importance. However, at the time of their construction a full understanding of the performance of these materials was still developing, so that they may present special problems of durability (poor cement mixes, inadequate cover to the reinforcement, etc.). The most delicate aspects usually concern the carbonation of the concrete (which hardens but becomes also more brittle, reducing its capacity to protect the steel) and the corrosion of the steel. Concrete exposed to chlorides (either in marine locations or from road salting) is often decayed and in this case there will be severe corrosion of the steel.

To consolidate a reinforced concrete element affected by these phenomena usually requires the elimination of the decayed concrete (water jet, etc.), the cleaning of the steel and the addition of new reinforcement. Portions of the structure can then be rebuilt, often using special concrete.
Part III

GLOSSARY

**Action n.** - Any agent (forces, deformations, etc.) which directly or indirectly produces stresses and/or strains into a building structure and any phenomenon (chemical, biological, etc.) which affects the materials of which the building structure is composed. The different categories of actions and their definitions are given in the “Guidelines”.

**Adobe n.** - Adobe comprises bricks made from clay and simply dried in the sun. Some organic materials like straw or animal excrement can be used to improve durability or reduce shrinkage.

**Anamnesis n.** - The account of the case history of a building including past traumas, interventions, modifications, etc. The research to acquire this information prior to examination. This is the first step prior to diagnosis. See Control, Diagnosis, and Therapy.

**Architectural Heritage n.** - Buildings and complex of buildings (towns, etc.) of historical value. See Building.

**Brick n.** - A brick is a masonry unit usually made of clay which can be fired or simply dried in the sun.

**Brick Masonry n.** - Brick masonry is a composite structure or material made of alternating brick courses set in mortar.

**Building n.** - Something that is built. When used in context of these “Recommendations”, the term encompasses churches, temples, bridges, dams, and all construction works. Also referred to as Architectural Heritage.

**Control n.** - A standard of comparison for checking the results of an experiment. To verify and regulate the efficiency of an enacted therapy through tests, monitoring and examination. See Anamnesis, Diagnosis, and Therapy.
Conservation n. – Operations which maintain the building as it is today, even if limited interventions are accepted to improve the safety levels.

Cost Benefit analysis - Costs and benefits refer to general rather than monetary terms. Costs can be measured also in the potential loss of fabric due to the invasiveness of the therapy, and benefits can be those gained by the therapy as well as knowledge that will prove useful in the future. This term should not to be interpreted as “value engineering”.

Damage n. - Change and worsening of the structural behaviour produced by mechanical actions or/and by the reduction of the strength.
Reduction of the mechanical bearing capacity related to the breakdown of a structural system. See Decay and Structure.

Decay n. – Change and worsening of the materials characteristics produced by chemical or biological actions. Chemical deterioration related to the breakdown of the materials of which a structural system is composed. Loss of quality, wasting away, decayed tissue. See Damage.

Diagnosis n. - The act or process of identifying or determining the nature and cause of damage and decay through, observation, investigation (including mathematical models) and historical analysis, and the opinion derived from such activities. See Anamnesis, Control, and Therapy.

Examination n. - The visual part of an investigation that excludes material testing, structural analysis, structural testing, and other more sophisticated investigative techniques.

Explanatory Report - A report that specifically defines the subjective aspects involved in a safety assessment, such as uncertainties in the data assumed, and the difficulties in a precise evaluation of the phenomena that may lead to conclusions of uncertain reliability.

Fabric n. - The structural and material parts that make up the building (frames, walls, floors, roof, etc.)
**Fired bricks** - A fired brick is ceramic material obtained by preparation, moulding (or extrusion) of raw material (clay) and subsequent drying and firing at an appropriate temperature.

**Geometrical Survey** - Survey sheets. Measured drawings (plans, elevations, sections, etc.) where the geometry of the building is identified.

**Heritage Value** - Architectural, cultural, and/or historic value ascribed to a building or site. Heritage value may have varying definitions and importance from culture to culture.

**Historical Approach** - Evaluation based upon historical research and past experience. See *Qualitative Approach* and *Quantitative Approach*.

**Holistic adj.** - Emphasizing the importance of the whole and the interdependence of its parts.

**Intervention n.** - The physical intrusion upon a building during a diagnosis, or its therapy.

**Investigation n.** - A systematic and detailed evaluation of a building that can include examination, material testing, structural analysis, and structural testing. See *Diagnosis, Examination, Material Testing, Structural analysis*, and *Structural Testing*.

**Maintenance** - A series of activities finalised to the conservation of the asset

**Material Testing** - Laboratory or field testing of materials (physical, chemical, porosity, accelerated weathering, etc.).

**Mortars** – A mortar is a mix of one or more binders, aggregates and water. Sometimes additives in certain proportions are included to give the mixture appropriate consistency and workability in the fresh state and adequate physical-mechanical properties when hardened.

**Multi-leaf masonry** – Masonry made of leaves of different constitution. (The most common is the three leaves masonry made of two external faces and an inner rubble core.)
Natural stones - Natural stones have been formed by geological processes. They consist of mixtures of minerals. Natural stones can be grouped according to their origin into magmatic, metamorphous and sedimentary stones (sandstone, limestone, etc.). Natural stones differ by origin, if their composition has not been altered by man.

Observational Method - An increment approach to intervene or to strengthen, starting from a minimum level of intervention, with possible subsequent adoption of a series of corrective measures.

Quantitative Approach - Evaluation based on analytic or scientific methods such as testing, calculations, and mathematical modelling. See Historical Approach and Qualitative Approach.

Rehabilitation – Process to bring a building to a new use or function, without altering the portions of the building that are significant to its historical value.

Repointing - Result of repair or restoration on a deteriorated joint. It can be homogeneous to the existing joint or made of different material (e.g. cement of polymer).

Restoration – Process of recovering the form of a building as it appeared at a particular period of time by means of removal of additional work or by replacement of missing later work.

Safety Evaluation (assessment) - Evaluation of the safety margins of a structure with regard to heavy damage, partial or total collapse. See Historical approach, Qualitative Approach, Quantitative Approach. The opposite of safety is risk.

Strengthening – Interventions to increase the bearing capacity of a structure.

Structural Analysis - Calculations, computations, computer analysis using mathematical models.

Structural scheme – An approximate representation (or model) of the structure, different, but close to the reality.
Structural Testing - Laboratory or field testing of structures (assembly and component testing, floor loading, shaking-tables, etc.).

Structural Typology - The types of structures interpreted as regards their structural behaviour and their capacity to bear loads.

Structure n. – The part of a building which provides the bearing capacity, sometimes coincident with the building itself.

Tell-tale - A device fixed across a crack in a masonry structure to indicate movement.

Therapy - The choice of remedial measures (reinforcement, strengthening, replacement, etc.) in response to diagnosis. See Anamnesis, Control, and Diagnosis.
Fig. 6 – Plan of the Mother of God main church (katholikon) in Gelati Monastery
The virgin temple
East facade
Fig. 66
A = New positioned reinforced lime-mortar ring
B, C, D = Possible positions of additional metallic belt reinforcing (to be studied)
A = new reinforced lime-mortar ring
B = dome wall
C = jacks for pre-stressing the dome