Extending the Lifespan of the Architectural Heritage

Prolongement de la durée de vie de l'héritage architectural

Verlängerung der Lebensdauer des architektonischen Erbes

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Giorgio Croci, born in 1936, has carried out research, studies and projects for the strengthening and restoration of historical buildings, e.g. the Coliseum and the Senatorio Palace in Rome, the Ducal Palaces in Modena and Genoa, the Castle of Spoleto, the Basilica of St. Ignatio de Loyola in Spain, the minarets and mosques of Samarkand and Cairo, Chephren's Pyramid, Egypt, and temples of Angkor.

SUMMARY

The paper describes some of the possibilities for strengthening and restoring historic buildings. Regardless of the cause of damage, the strategies for intervention are greatly facilitated when the actions are stabilised, rather than due to sudden or evolutionary phenomena. In this latter case it may be expedient to intervene on a step-by-step basis and to use a monitoring system to ensure that the desired results are attained. The potential offered by new techniques and modern technology, such as synthetic fibres, ropes and stainless cables and the possibility to regulate induced forces and deformations artificially mean that structural engineering can make a substantial contribution to extending the lifespan of historic buildings and monuments.

RÉSUMÉ

L'auteur décrit les possibilités de renforcement et réhabilitation des ouvrages historiques. Indépendamment des causes de dégradation, l'intervention est d'autant plus facile que la stabilisation des effets dégradants a pu se faire au préalable, afin de ne pas avoir à faire face à une reprise ou à une progression subite du phénomène destructeur. Dans ce cas, il peut être plus avantageux d'intervenir au coup par coup et, à l'aide d'un système de surveillance, d'observer un arrêt éventuel des dommages. Les ingénieurs civils disposent actuellement de techniques innovatrices - comme la régulation artificielle des forces et des déformations induites - et de nouveaux matériaux - comme les fibres synthétiques, les fils et les câbles en acier inoxydable - qui permettent d'intervenir de manière significative pour prolonger la longévité de monuments et constructions historiques.

ZUSAMMENFASSUNG

Der Beitrag beschreibt Möglichkeiten zur Verstärkung und Restauration historischer Bauten. Unabhängig von der Schadensursache wird der Eingriff sehr erleichtert, wenn die Einwirkungen stabil sind, anstatt dass sie plötzlich oder fortschreitend auftreten. Im letzteren Fall kann es vorteilhaft sein, Schritt für Schritt einzugreifen und dabei zu beobachten, ob sich die erhofften Ergebnisse einstellen. Dank neuer Materialien wie synthetischen Fasern, Seilen und rostfreien Kabeln und Techniken, wie der künstlichen Regulierung der erzeugten Kräfte und Deformationen, können Ingenieure einen bedeutsamen Beitrag zur Verlängerung der Lebensdauer historischer Bauten leisten.

1. INTRODUCTION

Ancient monuments are delicate structures that bear witness to our culture through the centuries, and even millennia, despite the fact that their original designs not always gave attention to the aspects of durability and safety.
However to extend the lifespan of a monument is not always necessary to carry out substantial works; it is often possible, after a thorough inspection, to intervene with a few carefully chosen measures that respect the monument's historical value.
On 17 November 1994, a scientific mission made an ascent of Chephren's Pyramid (Figure 1) to evaluate the role of temperature and wind in the decay of the stone and to assess the stability of some blocks that have been shifted by earthquakes in the past (Figure 2). On the one hand the survey contributed new and important elements for deeper understanding of the construction of the pyramid and, on the other, showed that, apart from the problem of weathering, no radical structural interventions were necessary, it being sufficient to add some supports in the same limestone to ensure the stability of blocks at risk.
A thorough survey of any monument is only the first step in studies that often include in-depth investigations and, in the case of evolutionary phenomena, careful monitoring of data. Three classes of actions may affect the stability of a building, either independently or in combination: static actions (forces, loads, ...), indirect actions, such as imposed deformations (soil settlement, temperature variations, ...) and dynamic actions (mostly in connection with earthquakes).
From the strategic point of view it is useful to consider the relationship between the actions involved and time; in other words, whatever the cause of the damage, different strategies should be followed according to whether the actions are currently stabilised, in evolution or of the type that may appear suddenly.

Fig. 1: The ascent of Chephren's Pyramid

Fig. 2: Shifting of a block on the top of Chrephren's Pyramid

2. STABILISED ACTIONS

2.1 The origins of damage

Some supplementary forces or stresses usually ramain even after the phenomena that have caused damage are over. Sometime one of the main causes may be the original design, since in the past the form and dimensions of buildings were not always decided on the basis of analyses and calculations: rather, past experience and the observation of instances of collapse and damage were the only guides available to the architects.
Safety levels may therefore be very poor, especially when well-tried designs were abandoned for experimentl ones. Gothic cathedrals are an outstanding example of such structures. The radical nature of their design not only contains intrinsic weaknesses, but also renders them sensitive to even low-level actions such as minor soil settlements, low-intensity earthquakes or wind pressure.

In the cathedral of Vitoria in Spain the main columns have been affected by significant levels of curvature and deformations: at mid-column level, these measure about 30 cm (Figure 3) and the deformations have detached some of the voults (Figure 4).

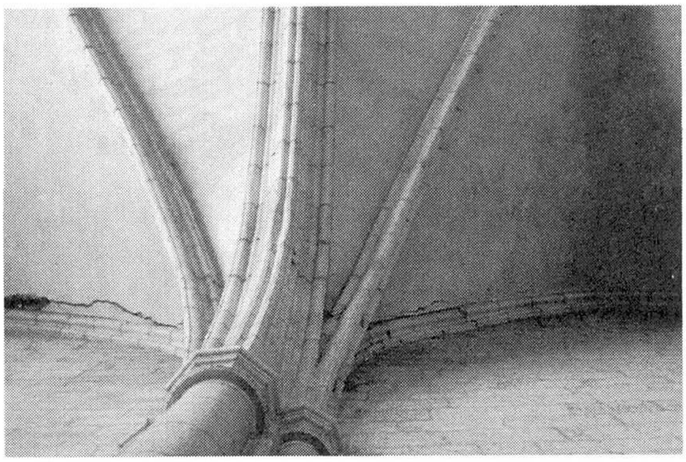

Fig. 4: Disconnections between the vaults and walls

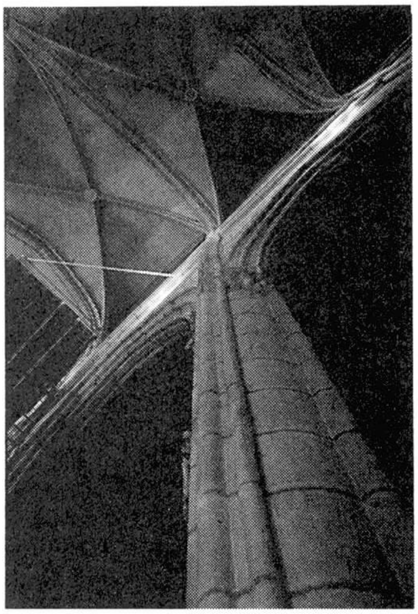

Fig. 3: Deformations on the columns of Vitoria Cathedral

A monitoring system recorded the evolution of temperatures, deformations and out-of-plumb, for one year, showing that the phenomena are now substantially stabilised.
A general elastic finite element model was used to clarify first the scarce spatial cooperation in this kind of structures and, subsequently, the influence of the sequence of construction on the resulting stresses and deformations (Figures 5 and 6): the results obtained were found to correspond well with the actual state of the building (Figure 3). However, it was also necessary to carry out a non-linear analysis, taking into account the influence of the weakest zones, such as the triforium, and reductions in the resistant sections of the columns in order to define present safety levels in terms of ductility.
The diagram in Figure 7 shows the equilibrium conditions in the middle section of the column, where the line "r" represents the resistant moment-curvature relationship and the line "a" is the external moment, taking account of the second order effects; the point "E" represents the equilibrium situation and the related curvature X is very close to the actual curvature measured. AMμ indicates the moment increment necessary to reach collapse, thus giving a very low real safety margin, especially taking into account possible errors in the evaluation of the limit deformations.

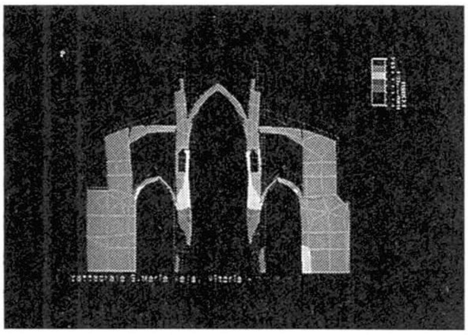

Fig. 5: Stresses and deformations where the buttresses were built before the vault

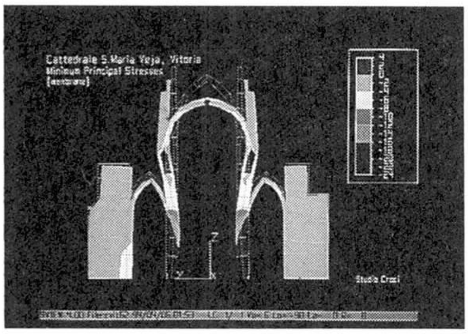

Fig. 6: Stresses and deformations where the buttresses were built after the central vault

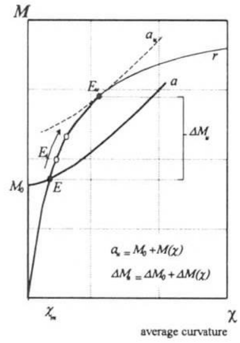

Fig. 7: Equilibrium between external and resistant moments

2.2 The strategy for intervention

Historic buildings in masonry often suffer from cracks and excessive deformations, of which the principal causes are usually the limited tensile strength and unbalanced thrusts.
The interventions can therefore conveniently follow these two main strategies: basis for the insertion of tie rods or cables and the introduction of artificial forces through the use of jacks or by prestressing.
The reinforcement measures carried out in the Cathedral of Vitoria are centred mainly in three areas (Figure 8):
- the tops of the pier extensions (a) will be longitudinally and transversely connected by trusses inserted in the garret to improve collaboration between the two sides of the nave and between the bays;
- the thrust assured by the flying buttresses in zone (b) may have been reduced by visco-elastic deformations: this will first be verified and if it is necessary to adjust the thrust by the use of flat jacks, a bidirectional counteraction will be assured by post-tensioned bars;
- finally, to stiffen the areas of the triforium and above the aisle vault springing (c), and make them more shear resistant, a truss will be inserted in the aisle garrets, which will be fixed to the buttresses and to the pier extensions.

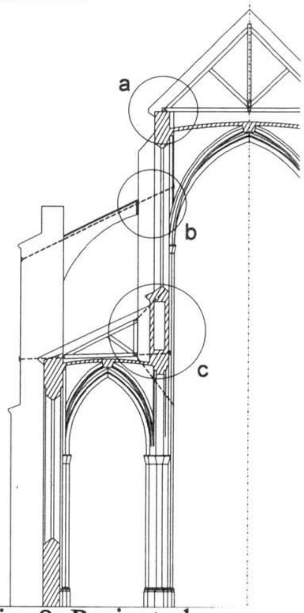

Fig. 8: Projected reinforcement measures

3. EVOLUTIONARY ACTIONS

3.1 The origins of damage

Soil settlement is the most common cause of evolutionary phenomena, often causing damage to monuments built generally on superficial foundations.
Although the soil itself may have thickened over the centuries and the original settlements are therefore extinguished, variations in the soil conditions and, particularly, in the hydraulic conditions (alterations to the natural drainage, raising or lowering of the water table, leakage from sewage systems, etc.) may well generate new settlements that are not easily stopped, since they often involve large areas, and whose further developments cannot easily be predicted.
Many of the monuments of Samarkand (Uzbekistan) are affected in this way and both minarets and disconnected walls have dangerous cracks or lean heavily. In the Tilla Kari Mosque on Rejistan Square (Figures 9 and 10) is an example in which the outward top displacements amount to tens of centimetres, creating unstable situations for both the walls and the connected vaults.

Figg. 9, 10: Leaning and deformations in minarets and mosques, Samarkand

3.2 The strategy for intervention

In consideration of the subsidence that involves much of the area of Samarkand and the difficulty of establishing a priori the entity of the measures necessary to stabilise the situation, it was proposed a step-by-step solution, using a minitoring system to check the improvements made during and after the completion of each phase and, finally, the stabilisation of the settlements.

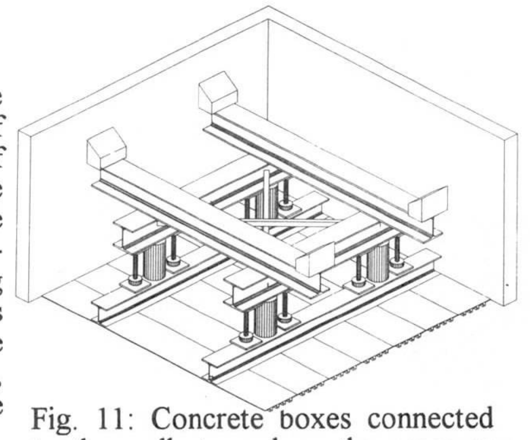

Fig. 11: Concrete boxes connected to the walls to reduce the pressure on the soil

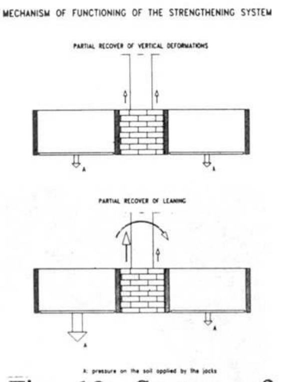

Fig. 12: System of Jacks to regulate pressure on the foundations

The solution consists in removing a certain amount of soil inside and outside the walls of the mosque and filling the spaces with empty reinforced concrete boxes, which are connected to the masonry foundations, so as to create a continuous rigid raft.
This has the dual advantage of reducing the weight and enlarging the foundations. A further significant advantage is obtained by placing a movable foundation slab on the bottom of the concrete boxes, loaded using provisional jacks (Figure 11 and 12) in order to induce and regulate the pressure necessary to correct the leaning on the basis of the data recorded.
If the settlement does not appear to stabilise, the movable and removable bottom slabs make it possible to dig more deeply in to the ground in different zones of the box girder and further reduce the loads, possibly reaching firmer strata.
This "observational criterion", based on a programme of step-by-step measures, by regulating the load and pressure on the soil at each stage, can eliminate the uncertainties inherent in predicting the possible evolution of soil settlements, making it more cost-effective.

4. SUDDEN OR UNEXPECTED ACTIONS

4.1 The origins of damage

These types of action include unexpected events such as bombing or landslides, or others that may be relatively probable, such as earthquakes or hurricanes.
General measures to mitigate the effects of disasters can prevent much of the loss involving ancient monuments. Earthquakes are the most prevalent phenomena for which preventive measures can substantially reduce damage and avoid collapses. The damage to monuments in Cairo caused by the earthquake of 12 October '92 offers an interesting example. Many minarets collapsed not only because the masonry was of poor quality but also on account of the intrinsic weakness of the structural behaviour, especially in the upper parts where slender columns cannot withstand both flexural and twisting actions (Figures 13 and 14). The connection between the minaret and the main part of the mosque is another weak zone, as is shown both by mathematical

Fig. 13: Slender columns in some minarets

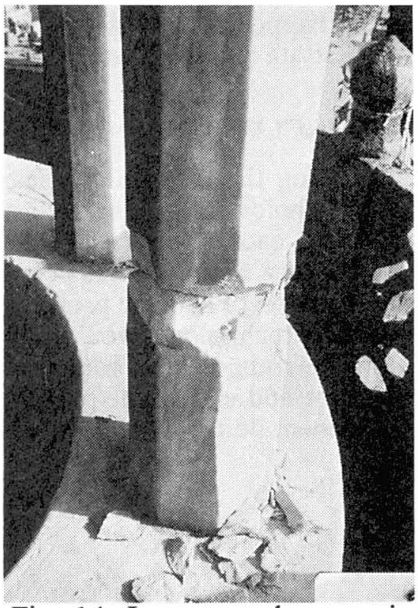

Fig. 14: Important damages in the upper part of a minaret

models (Figure 15) and direct observations, although the spontaneous cracks (Figure 16) automatically mitigate the seismic effects.

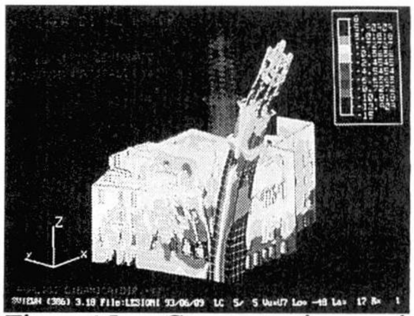

Fig. 15: Concentration of stresses and deformations revealed in a mathematic model

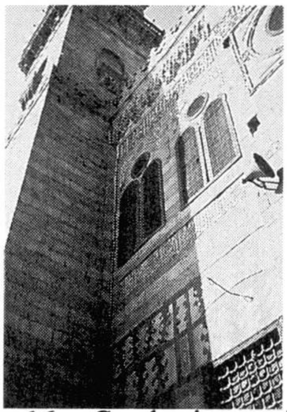

Fig. 16: Crack in a joint between the minaret and the mosque

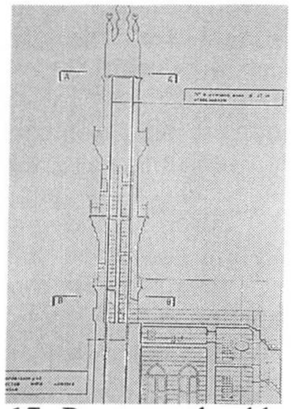

Fig. 17: Prestressed cables for the reinforcement of the minaret

4.2 The strategy for intervention

It is well known that seismic behaviour can be improved not only by strengthening measures, but also by reducing natural frequencies, improving the capacity to dissipate energy and reducing volumetric asymmetries etc.. In reality, however, it is not easy to reduce the natural frequencies (mainly stiffness) in historic buildings without penalising their strength; nor can the dissipation of energy usually be improved without introducing significant structural alterations such as creating joints between the structure and the foundation and replacing rigid connections with special dissipating devices.
The most suitable approach remains therefore strengthening, without renouncing anyway, when it is possible, to render different volumetric parts of the building independent of one another, such as by disjunction between the minaret and the mosque.
Besides offering an indispensable improvement in the masonry in specific areas where it has deteriorated, the reinforcement can usually be accomplished by tie bars, prestressed cables, etc. placed so as to confer appropriate tensile resistance. Figure 17 shows the strengthening of a minaret using prestressed vertical cables inserted inside the wall and requiring only small holes on the perimeter of the winding staircase. If the bearing capacity of the foundations is insufficient and if, as often happens, some degree of leaning is present, the cables can be anchored in deeper and more solid strata and a higher level of prestressing applied on the opposite side to the slant.

5. CONCLUSIONS

Extending the lifespan of ancient monuments is a challenging task that must take into account not only technical and economic aspects but also respect for historical values and the original concepts of building, each of which thus requires an individual solution. Nonetheless, each of the categories of phenomena examined has peculiar features that make it possible to define some general guidelines for the solution of specific problems.
Modern technology would appear to offer two principal possibilities: the use of steel or synthetic fibre tie rods, cables, ropes, etc. to give tensile resistance; and prestressing, springs, iacks, etc. to regulate and ensure the means of artificially inducing actions and, if need be, recovering part of the permanent deformations.