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Structural Aspects in Restoring Monuments

Aspects structuraux dans la restauration des monuments

Strukturelle Aspekte in der Denkmalpflege

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G. Croci, born 1936, has carried out important research, studies and projects for the strengthening and restoration of historical buildings. The Colosseum and Palace Senatorio in Rome, the Ducal Palaces in Modena and Genoa, the Castle of Spoleto, the Basilicas of St. Francis in Assisi and St. Ignacio de Loyola in Spain, represent some examples of his activity.

SUMMARY

This lecture highlights the different domains where structural engineering can contribute to the knowledge and restoration of Architectural Heritage. The assessment of the actual safety level of the monument is needed to decide on necessary measures. Objective and subjective aspects have to be taken into account. Whenever measures are needed, the advantages and disadvantages of the use of new or old materials and techniques are evaluated. The convenience of reversibility is examined. Finally, possible codes will be discussed to avoid misuse of existing codes which are not suited for this kind of structures.

RÉSUMÉ

Cet exposé traite des différents domaines où le génie civil peut apporter sa contribution à la connaissance et à la restauration du patrimoine architectural. La détermination de l'état de sécurité du monument permet de décider des mesures à prendre. Dans les cas où les interventions sont nécessaires, les avantages et les désavantages de l'usage de matériaux nouveaux ou anciens et les techniques correspondantes sont examinés. La réversibilité doit être prise en compte. La possibilité est envisagée de créer une norme afin d'éviter l'application de normes existantes mais inadéquates pour ce genre de structure.

ZUSAMMENFASSUNG

Es werden verschiedene Gebiete aufgezeigt, in denen der konstruktive Ingenieurbau wesentliches zur Denkmalpflege leisten kann. Die momentane Bestandesaufnahme ist notwendig, um über allfällige Interventionsmassnahmen zu entscheiden. Objektive und subjektive Aspekte sind zu berücksichtigen. Bei notwendigen Eingriffen werden die Vor- und Nachteile der Verwendung neuer oder alter Baustoffe und -techniken erwogen. Die Rückgängigmachung wird untersucht. Schliesslich werden Normen diskutiert, die den Einsatz heutiger, jedoch für derartige Konstruktionen ungeeigneten Normen verhindern sollen.

1. INTRODUCTION

The contribution of structural engineering in the study and design of restoration has been very important in the last few decades; from new investigation instruments to the most sophisticated monitoring networks, from information systems to mathematical models, from special devices for use on site to new technology and techniques for repairs. However the result of this large back-up has been only partially successful due to the unmethodical and often casual advances at the forefront of progress, the lack of interdisciplinary vision and insufficient cultural awareness; the result has been investigations seldom inserted within a coherent global program, the illusion of understanding the real behaviour on the basis of mathematical models which were not completely reliable, interventions carried out using new technology and materials that were not only insufficiently tested to simmulate the real conditions and thus ensure durability, but that also deeply altered the original conception.

Thus the time appears to be ripe for a general critical review of all matter and to face the main problems that can be reduced to two points:

- how to evaluate the safety levels of a monument and consequently how to decide whether or not interventions are needed;

- how to identify the criteria of interventions and the appropriate technology to use, taking account of the double requirement to alter as little as possible the original conception and to ensure safety and durability.

2. THE JUDGEMENT OF SAFETY LEVELS OF A MONUMENT

2.1

The evaluation of the bearing capacity, or more generally speaking of the safety levels, must be referred to three different conditions:

a) The Past. It is often useful to evaluate the safety levels of the original situation in order to understand if it was adequate at the time and if only subsequent deterioration or unexpected phenomena (earthquakes, soil settlements etc..) caused damage and failure. This evaluation helps us to find what the specific cause was. For example, in the case of the dome of St. Ignatius of Loyola in Spain, the structural analysis of the original "designed" form shows an irrational in the dome's shape, which is too hemispherical with a very heavy lantern on top; this causes high circumferencial stresses which generated the meridian cracks that are visible today. Although in the case of the St. Charles cathedral in Rome the crack pattern was similar, it was found, by means of a mathematical model, that as the shape was higher (figure 1), the dead loads could not have produced the cracks, not even taking into account thermal effects and seismic actions (in particular the strong earthquake of 1703). Further and deeper analysis, the observation of the cracks on the drum and the deformations of the cornice have shown that ancient soil deformations have been the determining factor; a monitoring system has shown that the deformations are now stabilized.

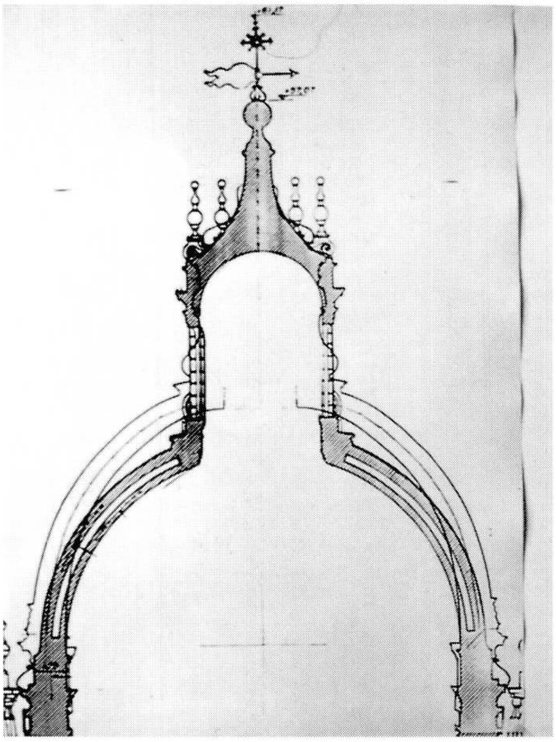


Fig. 1 Comparison between the shapes of St.Ignatius and St.Charles domes

b) The Present. The assessment of the present situation is the prerequisite for every intervention decision. In the above-mentioned dome of St. Ignatius, taking account of the cracks along the meridians, the analysis has shown large bending moments in the meridian arches, that result from the loss of circumferential continuity, and hence significant tensile stresses; thus we were obliged to develop a more sophisticated non-linear analysis that showed that only part of the section is in

Positions of the thrust within the thickness of the external shell, along the meridians, taking account of the reduced resistance of the sections

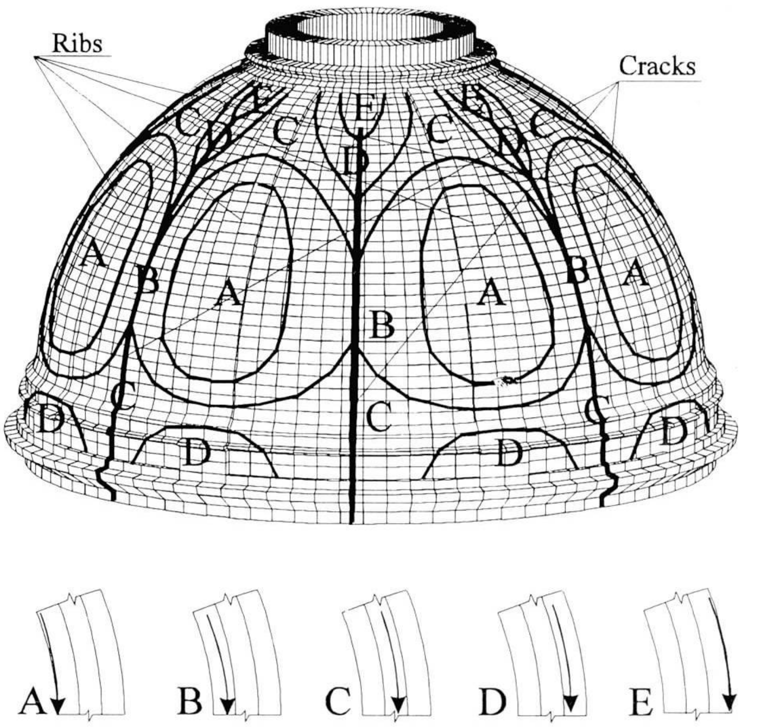


Fig. 2 St.Ignatius dome, cracks distribution and the results from a non-linear mathematical model

compression and that the safety levels are inadequate (figure 2).

c) The Future. The evaluation of the safety levels corresponding to various possible interventions gives not only a measure of the improvement of the behaviour, but also helps in the choice of the most appropriate criteria. In the Loyola dome it was easy to establish that prestressed circumferential cables are able to provide the radial pressure necessary to substantially compress the meridian section (figure 3).

2.2

The safety evaluation, however, is a very different task and cannot, unfortunately, always be obtained following mathematical analysis; on the contrary, this possibility is limited to very few simple cases. As a rule the process of arriving at a judgement is very complex and is acheived by an interlacing of objective and subjective aspects. There are three main routes to follow:

a) Observation of the reality. This process, which we may call the "empirical-qualitive method", lies in the survey of the monument as it stands today, through the observation of the quality of the materials, the crack and failure patterns, the foundation system, the ground morphology, etc.; this knowledge can be supported by chemical and mechanical tests and by data recorded on a monitoring system in order to highlight the evolution of various phenomena (figure 4).

The knowledge related to this process is linked to a subjective interpretation of the reality and is based on the comparison between what is now observed and what we have observed in the past in other constructions. From a philosophical point of view, this kind of knowledge can be included in the "inductive process category" upon which the observation of a great number of structures, failures and phenomena can lead to generalizations and thus, by means of synthesis, to a progressive enlargement of the knowledge itself, whose base is in experience. It was following this process that ancient builders were able to realize the great works of the past.

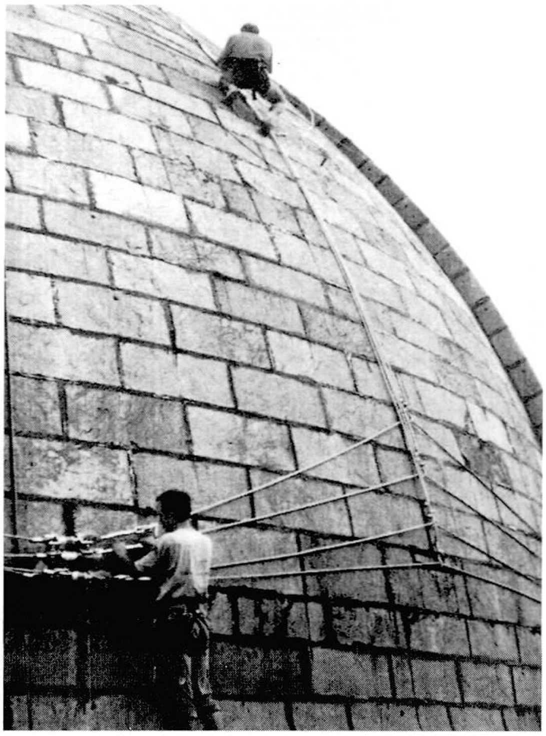
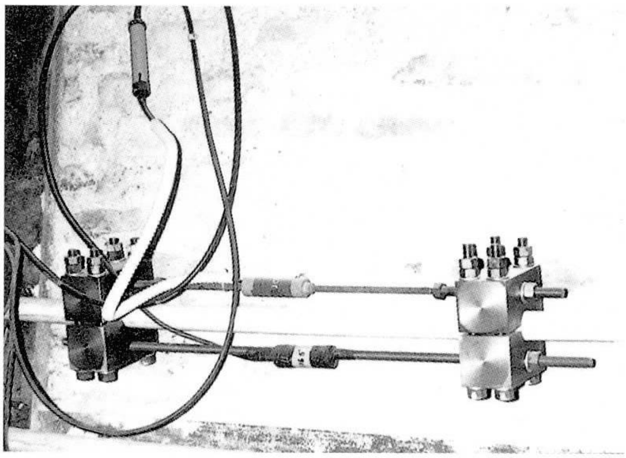
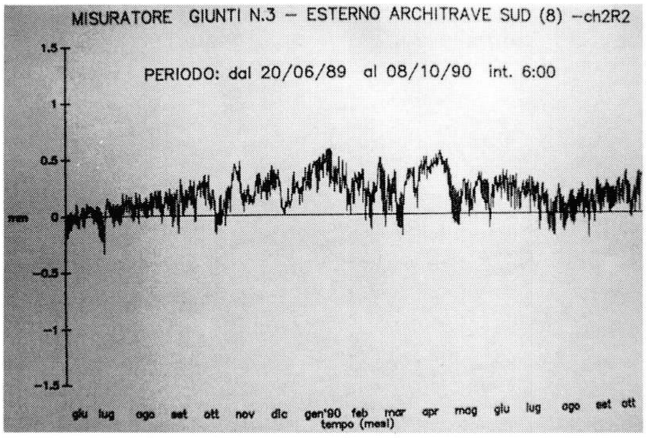


Fig. 3 Prestressed stainless steel circumferential cables



a)

b)



c)

Fig. 4 Monitoring system in the Loyola Basilica represented by: a network of instruments (a), a computer for data recording (b), results displayed in a time dependant diagram (c)

b) Mathematical Analysis. This process, which we can call the "theoretical-quantitive method", is usually based on the evaluation of the stress levels and deforfamations corresponding to different kinds of action (dead and live loads, temperature, soil settlements, earthquakes ....). In order to understand better the validity of this criteria, that from a philosophical point of view can be included in the "deductive process category", we must focus on the necessary compromise between a careful representation of the reality and the simplifications that are required to use the theories we have at our disposal.

This problem has represented a central point in the philosophy and in every cognitive process, in metaphysics as well as in epistemology: the possibility of connecting the subject with the object, the activity proceeding from the mind of man with real phenomena. From the conceptual point of view an important step has been realised by the the doctrine of "schematism" elaborated by Emanuel Kant in the "Critique of Pure Reason"; in his theory he attempts to overcome this apparent incomunicability by introducing an intermediate abstract element, the "scheme", which is accessible to the subject and representative of the object. In epistemology schematism is posed as a problem of scientific models, which are not only logical and mathematical constructions but also representations or imaginary pictures (i.e. schemes) of extremely complex structures. The scheme is located between theory and reality and is thus the only element capable of giving conceptual order and logical rigour to scientific knowledge.

c) Historical Survey. Last but not least this process is indispensable for a real knowledge of a monument. History provides an experimental laboratory on a real scale that we have yet to discover and decode by research, review and interpretation of historical documents, writings, drawings, photographs etc..

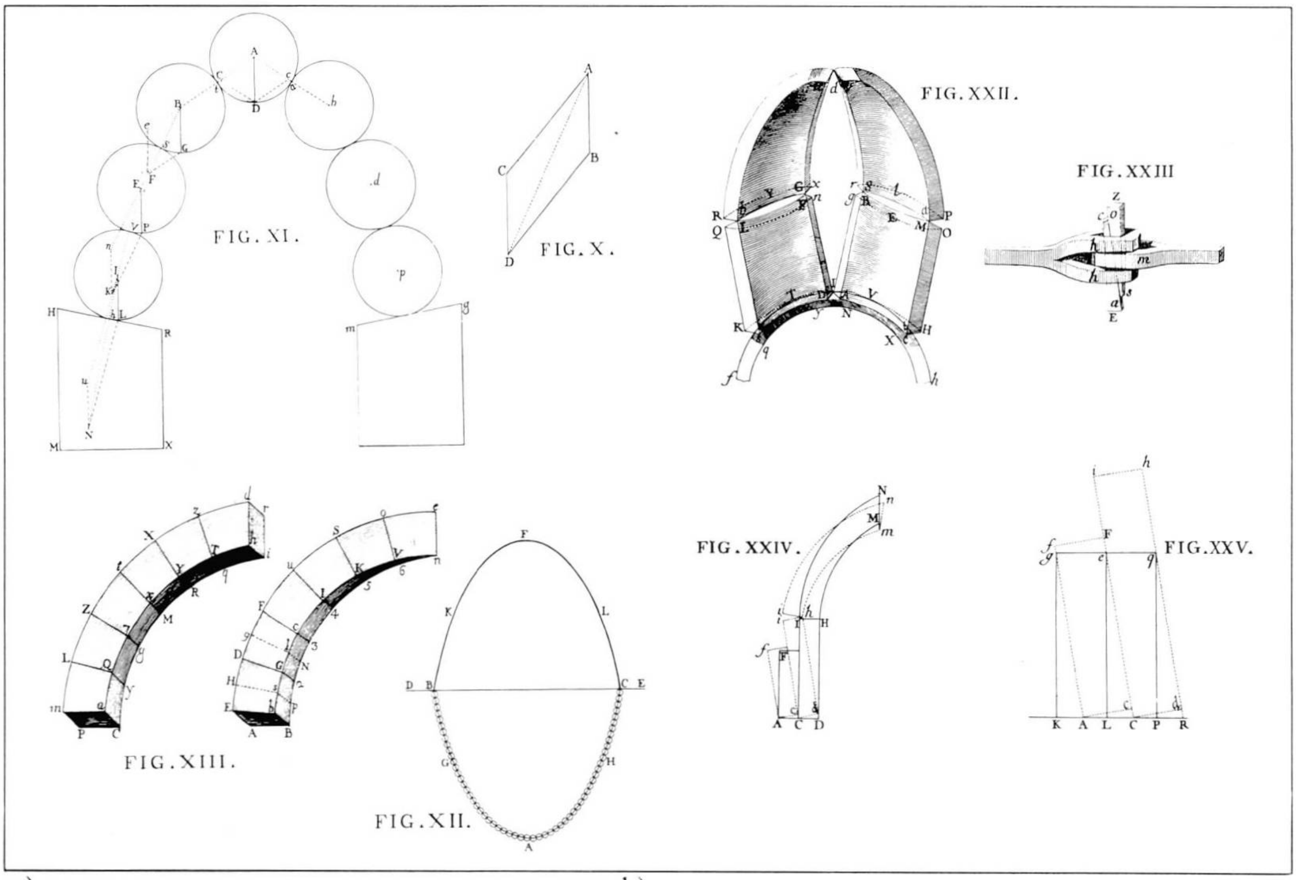
The main difficulty is that history was not written for structural engineering purposes and thus the objectivity of the facts must be partially rebuilt through the subjective reinterpretation of the researcher.

2.3

Thus each one of the three criteria we have mentioned contains both subjective and objective aspects. The perfect scheme is the reality itself; unfortunately we do not have objective mathematical theories to analyse it, so that only the subjective evaluation of an expert eye can give us a reliable approximation of the phenomena, and thus simplified schemes: the objectivity of the calculations do not provide objectivity in the knowledge.

Therefore we must acknowledge that mathematical models only furnish a support to the understanding, and not the understanding itself; the objectivity of the theoretical analysis is only apparant, as the choice of scheme is subjective and we know and accept that it provides a limited representation of the reality. Stresses higher than the resistance may not mean that the structure is unsafe, just as stresses lower than the resistance may not mean that the structure is safe; This limitation does not have solely negative aspects as it obliges engineers to overcome the boundary of theories and to enlarge their culture and the meaning of rationality itself; as Gaston Bachelard writes in "Le Rationalisme Applique": a knowledge of the non-rigorous must be restored so that a full comprehension of the rigorous may be possible.

This attitude tends to eliminate any argument between the supporters of the "theoretical" and "empirical" approaches that has continued throughout the centuries. One of the first disputes of this kind took place in 1742 when Pope Benedict XIV asked the opinion of "three Neopolitan Mathematicians" on the damages found of the dome of St. Peter's. The method they followed, that in a certain way sanctioned the official entry of science and mathematics into a field previously dominated by practice and experience, was extremely interesting: instead of using polygons of forces, they applied a primitive principle of virtual work to the dome, reduced to a rough mechanism, the cracks being likened to joints or hinges (figure 5). The results showed that the existing conditions did not ensure equilibrium and immediately became points of discussions; critics from among the



a) b)

Fig. 5 Structural analysis of St.Peter's dome from Poleni's "Historical Records of the Great Dome of the Temple" - Vatican 1748: a) theory of the curve of thrust, b) application of the principle of virtual work followers of the "empirical" approach responded "Michelangelo did not know mathematics but was still able to design the dome". However it is now time to lay aside sterile argument and to acknowledge that the value and reliability of the judgement, that simultaneously contains objective, subjective, quantative and qualitve aspects lies in the logic, rationality and the synthesis of the information available from the different processes, that is, experimental and theoretical analysis, historical survey and direct observation of the reality: a wider intergration of science and intuition, which Pascal called "l'esprit geometrique" and "l'esprit de finesse".

2.4

The impossibility to provide the "safety level" in the quantitative terms which structural engineering currently uses (limit state method etc..) poses new important problems, first of all the necessity of highlighting the different approximations involved in the study, that is to apply to the judgement an indication of the "reliability" of the judgement itself. Besides, if the "reliability" is low, we have to indicate if the approximations of the schemes and the simplified hypotheses have been made on the side of "prudence". This aspect is important because if a severe judgement leads to over-dimensioned interventions, but at the same time it has a low level reliability and we have been very prudent in the choice of scheme that determines the connections, restraints etc., we have to review the judgement itself and, if possible, to reduce the uncertainties by deeper analysis, investigations, etc..

Deeper investigations and stronger interventions can therefore be alternative options and we can decide the best route to follow on the basis of a general cost - benefit analysis.

In the case of the Colosseum, for example, it was the historical research which highlighted the role of earthquakes in the collapses; elastic finite element analysis, although "prudent", described extensively the initial behaviour and indicated the presence of the relevant tensile zones; the direct observation showed important permanent deformation and out-of-plumb, definitely related to earthquakes. It has been the synthesis of the information allowed us to first hypothesyse and then to verify that the process of the collapses has been progressive in two different ways: firstly during the main earthquakes of 443, 801, 1349 and 1703, that although of similar magnitudes found the monument in weaker and weaker configurations; secondly, "spontaneously" over the centuries with increasing rate as the cracks and the deformed structure facilitated and accelerated the deterioration. To try to follow all this by mathematical models in more "reliable" way, taking into account non-linearity, second order effects, residual stresses corresponding to permanent deformations, energy dissipation due to sliding of the blocks during an earthquake, differential soil settlements and seismic amplifications, linked to the heterogeneity of the foundations, that affect one part of the structure with respect to the other, is not possible; in any case, it would be extremely complicated and time consuming. Following these types of analyses can be the object of studies and research but not a realistic approach for ordinary engineers.

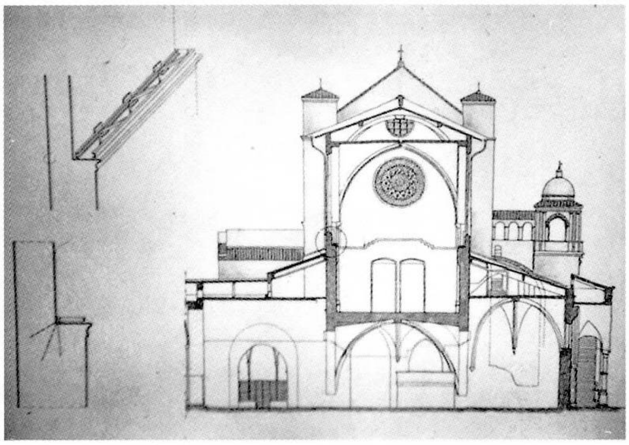
3. CRITERIA AND TECHNOLOGY FOR INTERVENTIONS

The decision of interventions and the time limit for their realization (each structure can be in a safe condition for a very short period of time and at risk for a very long period), is the consequence of the judgement on the safety of the monument. Some points must now be analysed:

a) - Historical Value and Risks. Monuments are precious objects that must be respected and altered as little as possible; this statement can lead, however, to some contradictions as higher risks must sometimes accepted, to avoid or limit modifications to the original conception. These risks depend on the one hand, on the minimum level of interventions, that related to the incertitude of the safety judgement, can become insufficient, and on the other hand on a delay of the decision in order to carry out deeper and deeper investigations. The case of the leaning tower of Pisa belongs to this category; although long since declared a building at high risk, until now it has not been acceptable to intervene on the foundations, where, with the available modern technology, the problem could definitely be solved. This possibility is the final option following only after more detailed studies and investigations show that the regulation of the water table and/or other soil improvements are not sufficient. But paradoxically, this respect of the historical value delay the solution of the problem and the tower is currently left in high risk without provisional shoring.

b) - Reversibility. Nowadays the cultural trend is for interventions to be reversible, that is to allow for the possibility of their removal. In principle this philosophy is correct, taking account of the fact that judgements are not always sufficiently reliable and it therefore seems useful to allow for the possibility of applying better techniques and materials that will become available. This kind of philosophy has been proposed in the restoration of the basilica of St. Francis in Assisi, where it was revealed that earthquake forces, and in particular the component normal to the lateral walls, created cracks in the walls which support the Giotto frescos. Reinforcement has been designed in order to limit deformability and thus the damages that periodically affects the frescos; this reinforcement consists of a steel trussed beam placed over the cornice. The restraints between the steel beam and the walls are realized by oleodynamic devices so that relative movements are allowed under normal conditions, but the restaints become rigid, and thus effective, under dynamic actions (figure 6).

a)



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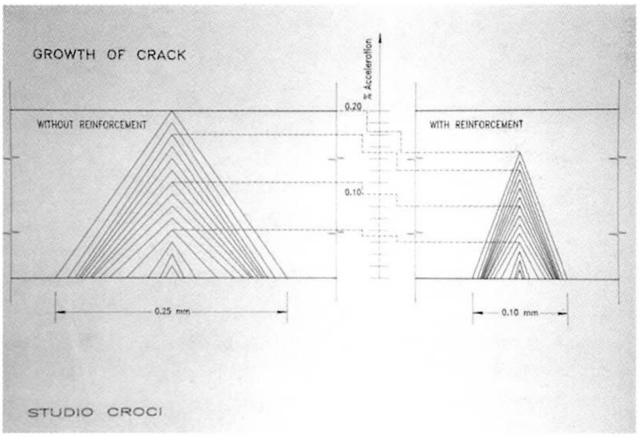


c)

Fig. 6 The Basilica of St.Francis of Assisi: a) vertical cracks that affect the walls, b) position of steel trussed beams over the intermediate cornice, c) reduction of the aperture of the cracks following the intervention

Another "reversible" intervention has been proposed for the reinforcement of some leaning minarets in Cairo, where six prestressed vertical cables will be placed along the interior perimeter, only creating small holes to cross the steps (figure 7).

It is important to note, however, that this philosophy must be accepted as a guideline rather than a compulsory method: situations where reversibility is neither possible or convenient are not infrequent, as, for example, the reinforcements of floors, the connections between walls and the strengthening of deteriorated masonry with appropriate grout injections.

c) - Ancient Technology. This can contain much more wisdom than appears from a superficial analysis: the deformability of the masonry, increased by microcracks or small cracks, that do not compromise the stability, but allow adaptation to minor soil settlements; the exceptional bearing capacity of arches, vaults and domes, if the thrust can be contained; the intelligent use of wood, not only in floors and roofs, but also as ties to improve the continuity and connections in the walls (figure 8). The use of old materials and technology in restoration projects is therefore not only appropriate for retaining the historical value, but also as an admission of their validity and worth of

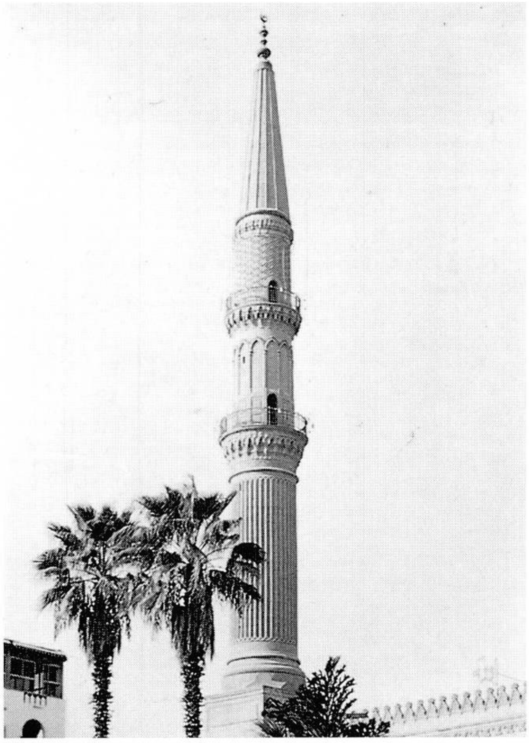
a)  b) 

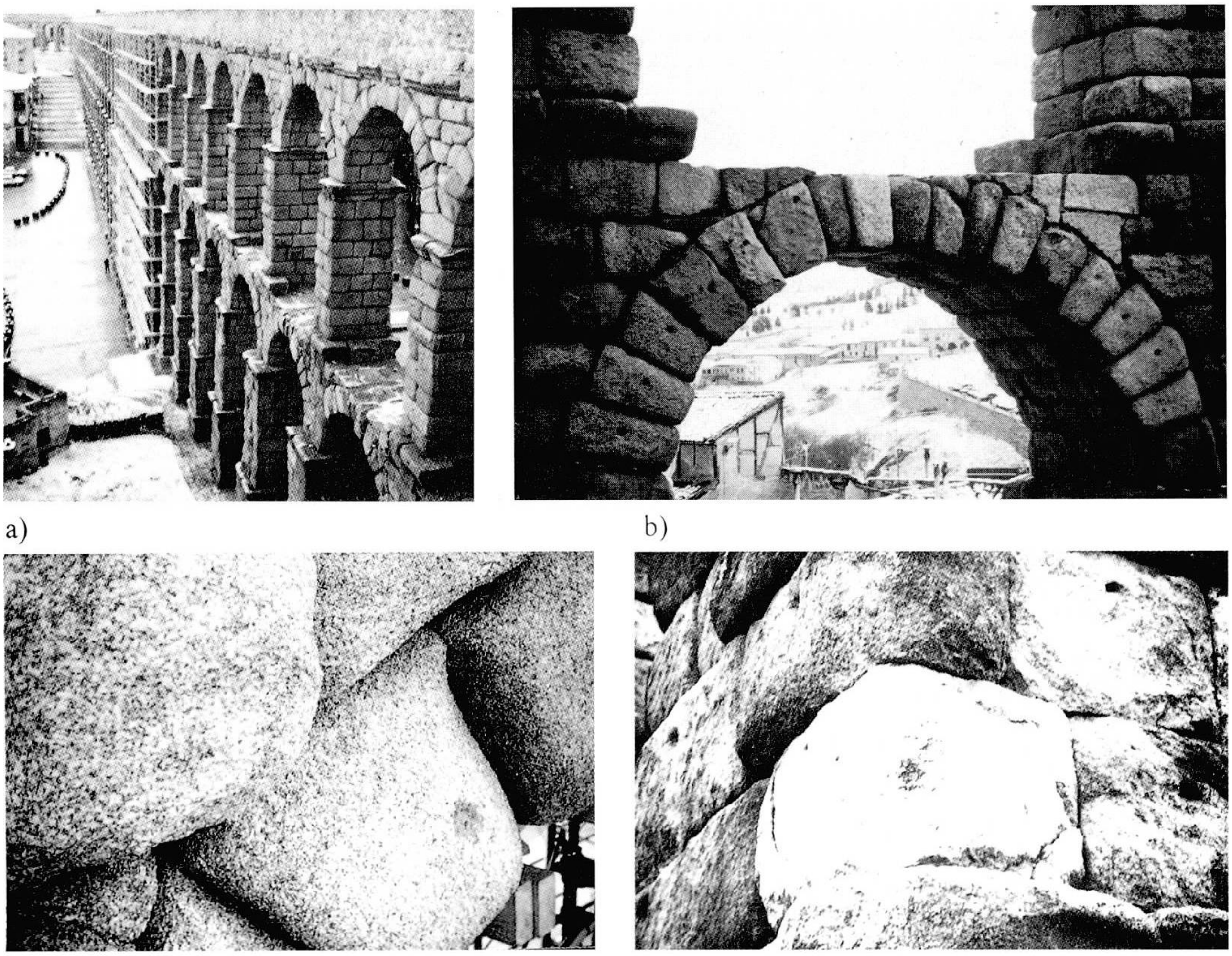
Fig. 7 Minarets in Cairo: weakness (a) and slenderness (b), often worsened by out-of-plomb

the original concept. In many cases it is just the passing of time and/or the anthropic activity that produce natural deterioration, whose rate has recently increased due to changes in enviromental conditions such as pollution, traffic, increases in population, etc.. The two thousand year old aquaduct of Segovia is still structurale sound and the real problems have been recently created by the traffic pollution (figure 9); the granite blocks, superposed without mortar allow small adjustments for the redistribution of stresses and do not contrast the thermal deformations. Restoration works must never change this behaviour and it will be necessary to reorganize the traffic in the downtown to radically solve the problem. The more than four thousand year old Chefren Pyramid (figure 10) only suffers from the consequences of a very slow but continuous eolic erosion, fortunately in dry conditions; the fall of some blocks during the earthquake of October 1992 is only the result of a lack of maintenance; it will not be necessary to use especially strong structures to fix the blockwork, but it will be sufficient to recreate the connections using the original materials and techniques, that have so successfully defied the millenia.

a) b)

Fig. 8 Wood chains to connect the walls (a) and to counteract the thrust at the base of a dome (b)



a) b) c) d)

Fig 9 The Aquaduct of Segovia (a), where the perfect equilibrium of arches (b) has not been compromised by the rounding of the blocks edges by two thousand years of snow, rain and eolic action (c), but whose survival is at risk from pollution (d)

Old conceptions and old technology are not however faultless: it could be sufficient to think that the history of Architecture includes the lesser known history of damages and collapses, on the basis of which the soundest solutions have been found. Imperfect design (as in the case of the shape of the St. Ignatius dome mentioned above), lack in the continuity of the walls, especially at the corners, insufficient tensile strength of the masonry and irreversible deterioration, especially of timber elements, are just some of the problems that we heritage from the past.

In some situations, such as the Monastry of Mar Mousa in Syria (figure 11) deterioration is so high that it will be very difficult to reduce the risks to a level that a modern society requires using ancient technologies alone, especially regarding the precarious conditions of the foundations.

Therefore it must be an intelligent rather than rigid position, to evaluate in each specific case, the degree of convenience of using the original technology and old materials, also referring to the presence of new phenomena (soil settlements, earthquakes..).

d) - Modern technology. The recent and frequent use of new technology and techniques has brought about a reaction against them, that, however, as all rigid standpoints, can not always be justified. Certainly new technology should be used with a high degree of care, because its power can create irreversible damage, as can be observed in projects of the recent decades; this is made worse by the fact that much of the new technology (i.e. the insertion of steel bars in masonry, cement injections etc..) has not been throughly tested before being used in monuments and has often been applied where unnecessary without understanding the possible unfavourable side effects.

a)

b)

c)

d)

Fig. 10 The Chefren Pyramid (a) suffers from a lack of maintenance; the progressive destruction of the weak mortar and the more fragile blocks (b) has created dangerous conditions (c). The earthquakes have accentuated this situation, making some blocks fall and moving the very top (d)

Fig. 11 Monastry of Mar Mousa in Siria: deteroration of the masonry and dangerous disintegration of the stone basement

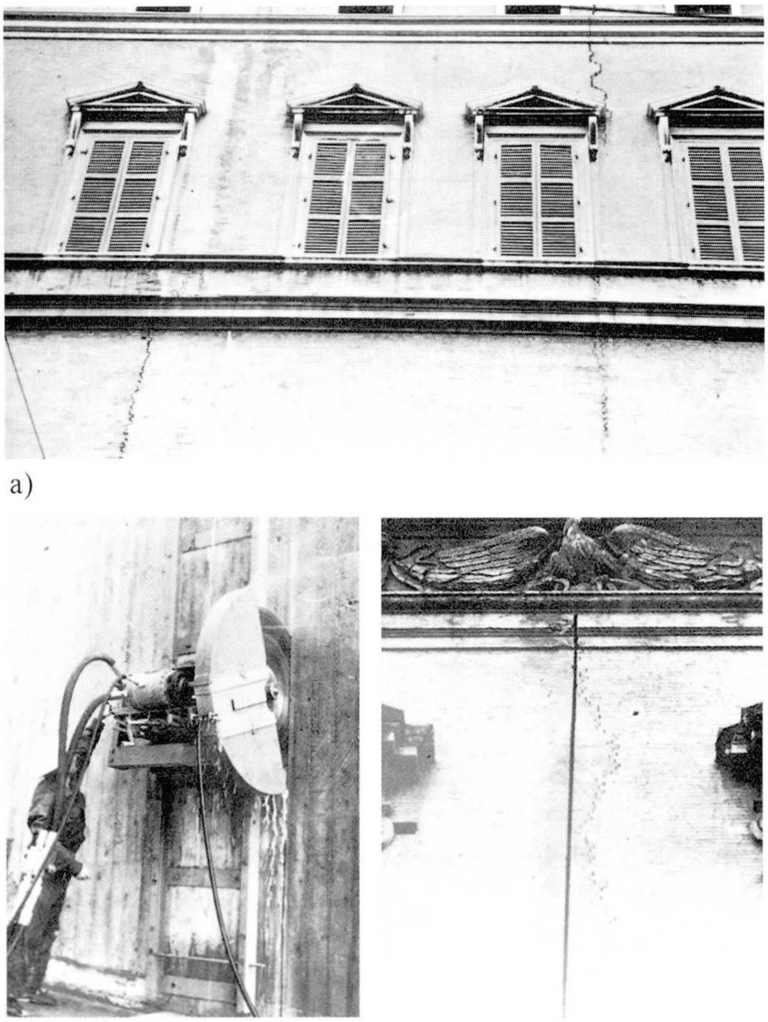
Cases of restoration works to put right what was recently restored are not unusual. The restoration branch of engineering, must make choices on the side of prudence and must be integrated by a large cultural view, where there is place for Science, History and Architecture, in order to evaluate the meaning and the consequences of any alterations to the original conception. We think anyway that, if properly used, modern technques and technology can give interesting solutions and help in the preservation architectural heritage.

The following examples highlight some significant applications.

The Ducal Palace of Modena (figure 12) was affected by significant subsidence phenomena. Fifteen years ago the problem was solved by making vertical cuts in the Palace following the main cracks in the walls, the movement joints that have been thus created allow the building to follow the soil settlements without further relevant stresses or cracking to the structure. The result has been completely satisfactory.

The Ducal Palace of Genoa (figure 13) suffered from foundation deformations that affected the main façade creating a loss of curvature in the main vault of the salon; the problem required the creation of an efficient connection between the opposite façades and the assurance of the stability of the vault. This was resolved by the placing of a steel arched beam, placed between the vault and the roof. This arched beam works simultaneously as a tie between the walls (for this reason an appropriate stiffness is required) and as a support for the vault by means of small connecting rods. A monitoring system, installed for a year, checked the intervention and particularly the stresses in the connecting rods; the results showed important thermal effects which lead to the replacement of the rods with springs, in order to maintain a constant supporting force. The monitoring system has been thus not only a way of control, but also a support for the final design.

One of the most important problems in restoring monuments is often the need to assure a certain level of tensile strength; modern materials can sometimes offer interesting and more efficient alternatives to the ancient iron chains, the wood ties or the weak connections realized in masonry itself.



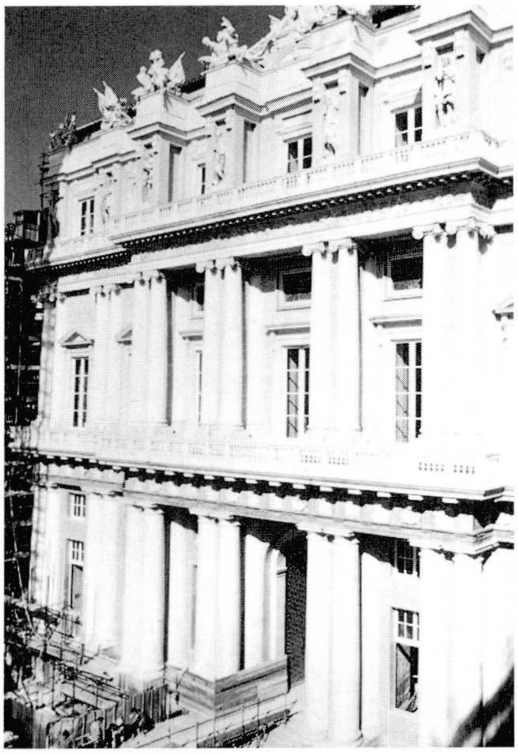
a) b) c)

Fig. 12 The Ducal Palace of Modena: relevant cracks in the walls due to soil settlements (a), special device for cutting walls (b) and the realization of joints (c)

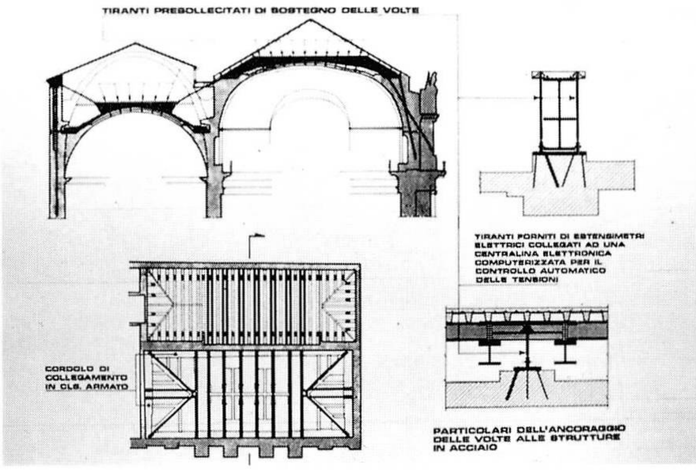
In the dome of St. Ignatius of Loyola, small prestressed stainless steel cables, normally used to sustain the masts of sailing boats, were used, having the advatages of economy and durability (figure 3); In the basilica of St. Mary of the Angels in Assisi synthetic fibre ropes of polypropilene, made by Retiflex, were used in the exterior walls (figure 14), with the double purpose of giving transversal resistance to the walls and connecting them to the façade; an appropriate pretension assured the immediate efficiency, while the very low modulus of elasticity (approx. 20,000 kg/cm2) of the same order of or less than that of the masonry, avoids zones of stress concentration and does not modify the stress distribution in the compressed zones.

Prestressed steel cables offer a wide range of applications: in Palazzo Altemps, in order to rid the main ancient saloon of subsequently constructed internal walls whilst supporting the floors that bear onto them, prestressed cables were used to reinforce the upper part of the walls that now work as beams (figure 15).

We want to mention, finally, that new technology can be very useful when the recovery of a deformation or out-of-plumb is required A system of jacks connected with a monitoring system, is currently being used while work is in progress on the foundations of the St. Michael Palace in Rome. A similar system is used to control the archeological excavation works beneath the foundations of small houses built centuries ago over the roman amphitheatre of Ancona (figure 16): a serie of provisonial steel elements created under the foundations, step by step, allow the progression of the excavation before choosing the final solution. In the Cathedral of Vitoria in Spain (figure 17)



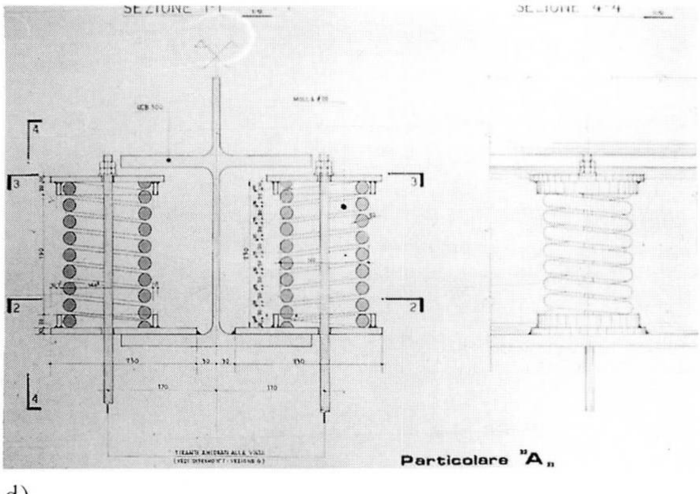
a)



c)

Fig. 13 The Ducal Palace of Genoa: the outward deformation of the façade (a) created by a loss in the curvature of the voult (b); the intervention (c) realized the connection between the opposite walls and support by means of springs (d) to the vault

b)



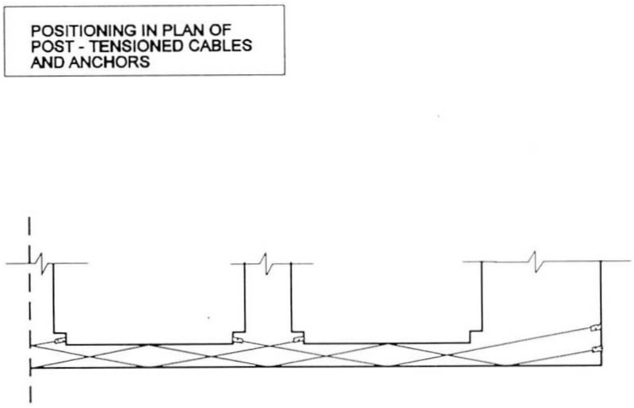
d)

provisional steel elements connected to a monitoring system are going to be used to recover the huge deformations created by ancient soil settlements.

In conclusion new technology enlarges the range of choice and can offer a very useful support: it is to the culture of engineers, architects and all people involved in the preservation of Architectural Heritage to profit from this possibility in the right way.

Fig. 14 St. Mary of the Angels in Assisi was affected by seismic cracks (a) and has been reinforced with synthetic fibre (b); the diagrams show the improvement in the seismic resistance capacity calculated by non-linear analysis (c)

a)



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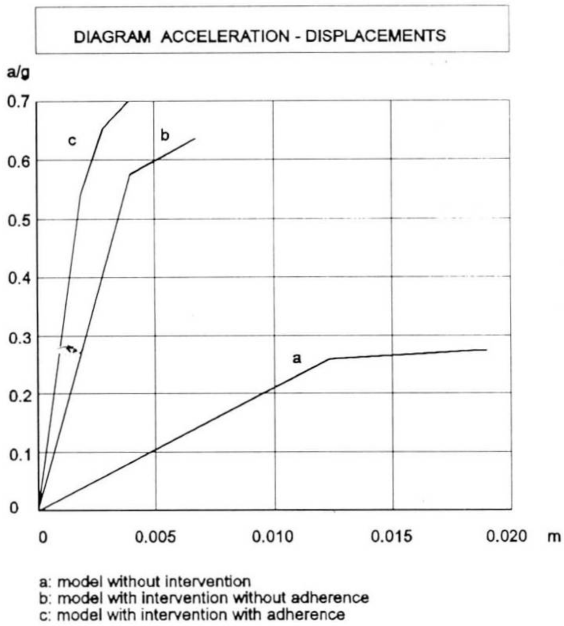

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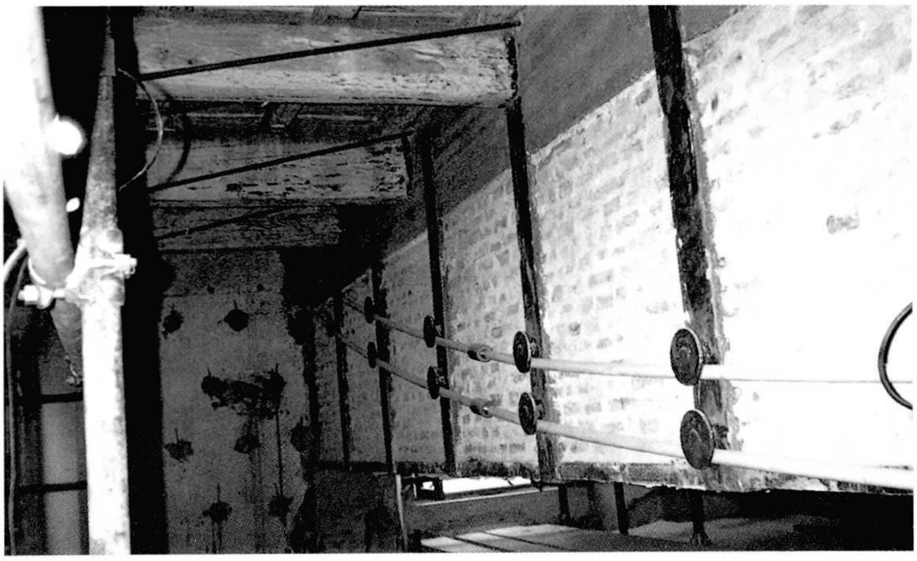
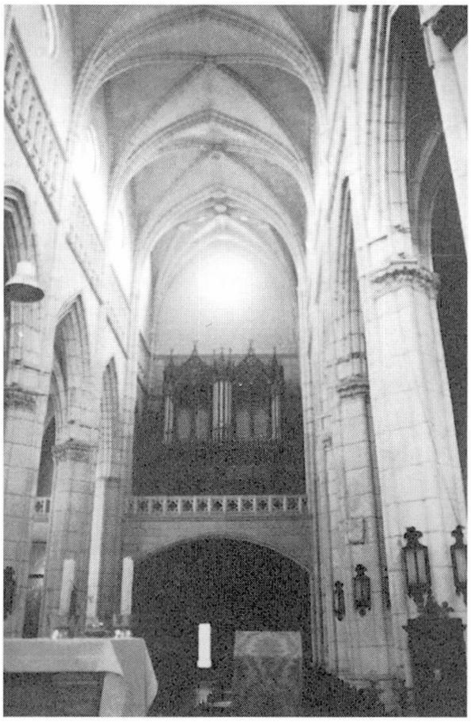


Fig. 15 Palazzo Altemps: prestressed cables to reinforce the remaining upper part of a demolished wall, working now as a "beam", to allow support for the floors above

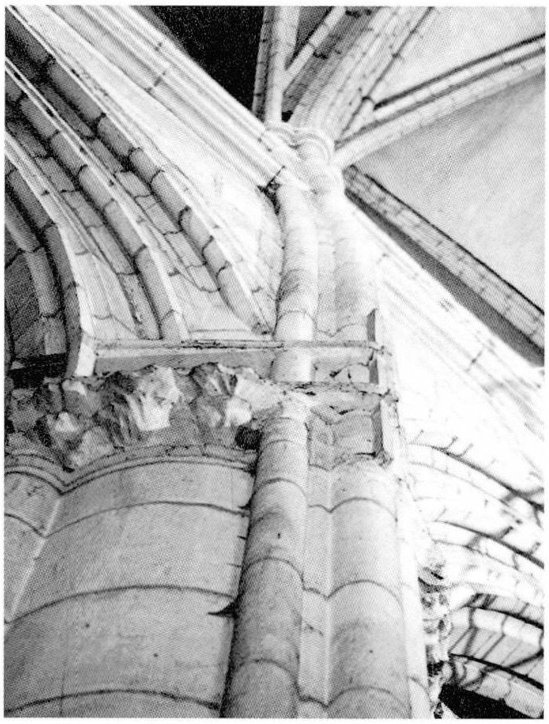
a)

b)

Fig. 16 The Amphiteatre of Ancona with houses built above (a) and excavation works under the foundations (b)



a)



b)

Fig. 17 The Cathedral of Vitoria in Spain (a) and the huge deformations of the columns (b)

4. A NEW PHILOSOPHY FOR A CODE

It is unquestionable that a code for investigations, analysis, projects, works, controls, etc.. would not just be useful but is absolutely necessary. The lack of guidance allows us to propose solutions that are often based on arbitary decisions without proof of the benefits or preliminary experimentation to discover the possible side effects. Besides which, as quality control is not always requested, there is no certitude that the expected results will be attained. The lack of a specific code is also the cause of misunderstanding and leads to the inappropriate use of other codes that are aimed for different purposes. The seismic codes created for new constructions or for the repair of seismic damages in ordinary buildings for example cannot be used, either for the characteristics of the actions (the behaviour of a monument under seismic loading is very particular) or for the techniques often proposed (extensive use of reinforced concrete,...). This problem occurred in Dubrovnik where, after the bombing of December 1991, we began to study various buildings with the view to designing restoration interventions (figure 18); as Dubrovnik is in a zone of strong seismic action, and we must follow the Croatian Seismic code, we will be obliged to introduce reinforcement heavier than that required for the repair: therefore the code risks being as damaging as the bombs, creating alterations that may compromise the historical value which has been preserved for centuries.

A similar problem is posed in the restoration of the historical walls of Urbino (figure 19), largely damaged and with a part that has recently collapsed. Calculations following the usual Code on the retaining walls show that the earth pressures are higher than the Urbino walls are capable of supporting; the designers and administrators have been left with a difficult choice, between accepting lower safety levels, thereby breaking the law or carrying out interventions that will presumably be stronger than necessary thus substantially modifying the original conception

In conclusion we can see that creating a Code expressly for the Architectural Heritage is necessary but at the same time a very complex task and thus requires a global rethinking of the overall philosophy of safety evaluation, of the reliability of the judgments and of the responsibilities involved.

a)

b)

Fig. 18 A view of Dubrovnik (a) and the damages after the bombing in December 1991 (b)

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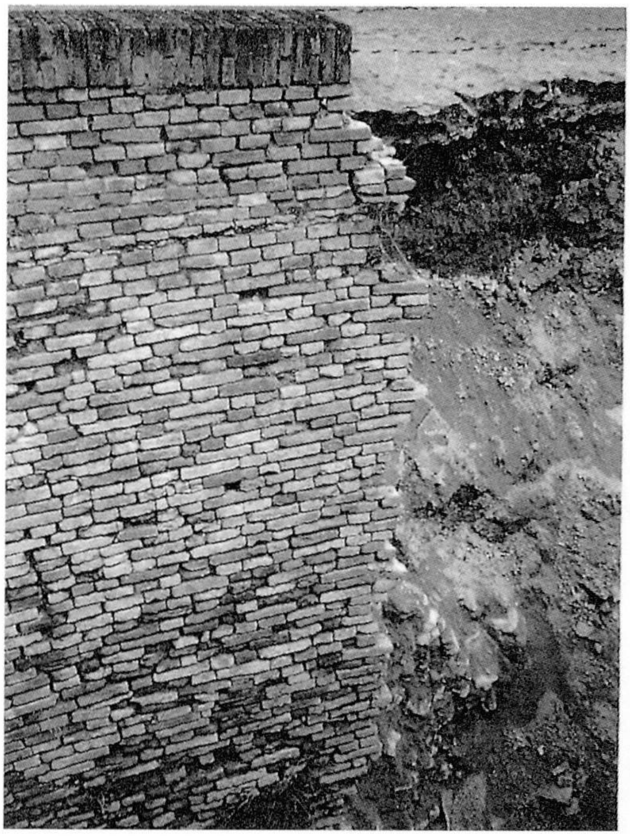
Fig. 19 A view of the Urbino walls (a), a collapsed zone where it is possible to see the poor condition of the masonry (b, c)

a)



b)

c)