Structural restoration of historical buildings in seismic areas

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Summary

Techniques, materials and design procedures in use for the structural restoration of historical buildings and monuments in seismic areas are presented on a conceptual basis and in relation to the restoration principles as they are stated in the Venice Charter. In this respect, the dependence of the restoration on the preservation of the aesthetic and historical values of the buildings, the low reliability of their original textures and the limitations to the intervention materials and techniques, create a very strict frame of actions, which is a real challenge for the structural engineer.

Key words: restoration techniques; restoration materials; restoration procedure; structural restoration; monuments and earthquakes; monuments and seismic protection; historical buildings and earthquakes

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Introduction

The objective of this paper is to outline the techniques, materials and design procedures in use for the structural restoration of historical buildings and monuments damaged by earthquakes. These structures are all those which merit special care on account of their individual historical or architectural importance or their significance as surviving representatives of an earlier tradition.

Generally speaking the problem of restoration of these buildings differs radically from the problem of repair and strengthening of ordinary buildings. For monumental buildings emphasis is given to the preservation of their *aesthetic* and *historical values*, while the task to remain in use may be considered of secondary importance, and in any case as a consequence of the effort towards fulfilment of the main task. So, the aim of the restoration according to the Venice Charter[1] is to *preserve* and *reveal* the aesthetic and historical values of the monument or historical building.

Particularly for structural restoration, the basic principles that should be taken into consideration may be listed as follows[1]:

- respect for original material and authentic documents;
- respect for the valid contributions of all periods to the building;
- replacement of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original;
- additions cannot be allowed, except in so far as they do not detract from the interesting parts of the building, its traditional setting and its relation with its surroundings;
- the use of traditional techniques and materials is *clearly preferable* for structural restorations;
- modern techniques and materials are admissible where adequate capacity cannot be ensured by traditional techniques. In this case *durability* and *compatibility* of the interventions should be adequately proven; otherwise the modern techniques and materials should be used only in a manner that will permit easy corrective action at a later date if necessary (*reversible* intervention);
- measures are necessary to protect and safeguard fresco and mosaic decoration. This may exclude the use of some strengthening techniques that may cause damage.

Techniques for structural restoration

Keeping in mind what has been presented already and what is included in Article 10 of the Venice Charter, it is concluded that the intervention procedure is an action of high complexity and requires special techniques, materials and design procedures appropriate for each case. It should be noted from the beginning that there is a strong relation between techniques and materials to be used in the intervention scheme and those of the existing monument which is being restored.

CLASSIFICATION OF TECHNIQUES

Restoration techniques may be classified in two categories[2]: *reversible* and *irreversible*. Generally, reversible actions are preferable for the following reasons:

- if they prove inefficient or of low durability they can be replaced without damage to the original fabric;
- if better techniques or materials are developed they can be replaced easily;
- The artistic or historical evidence is not falsified;

The following techniques may be classified as reversible actions:

- external buttresses;
- ties at the springing of arches[3];
- rings at the base of domes (Fig. 1a,[3]);
- prestressed unbonded stitches;
- restoration of stone or marble monuments with dry joints;
- external ties[4,5];
- internal steel curbs for confinement;
- improvement of the strength, stiffness and ductility of existing diaphragms (Fig. 1b,[6]), etc.

The materials for these techniques usually impose very few restrictions on the structures. For example, the external rings or ties need special care only at the points of connection with the original fabric, and encounter compatibility problems due only to the different coefficient of thermal expansion. So, in reversible techniques all modern materials may be used without serious limitations.

Despite these advantages, reversible methods are not always realistic or applicable. Furthermore, it may not be possible to solve an existing restoration problem simply by reversible interventions. On the contrary, interventions are mainly *irreversible*, particularly in the case of masonry buildings where the re-establishment of their integrity is of prime importance. The significant feature of this type of intervention is that they cannot be easily undone without damage to the original fabric.

The following techniques may be classified in the category of irreversible actions:

- grouting;
- bonding-in of new bricks across cracks after grouting and cutting out to each side (Fig. 2a);
- deep rejoints (Fig. 2b);
- rebuilding of part of the facings of walls where these have fallen bodily;
- stitching of walls with prestressed rebars;
- reinforcement of masonry with incorporated steel bars (*reticolo cementato*), (Fig. 2c,[7]);
- interconnections of marble or stone parts with bonded dowels;
- skins of reinforced concrete on masonry walls on upper sides of vaults;
- strengthening of foundations, etc;
- reinforcement with fibre-reinforced plastics (FRPs)[8];
- underpinning.

Among these mentioned techniques, grouting, bonding-in of new bricks across cracks, deep rejoining and rebuilding of masonry walls are the most usual and the most extensive interventions since this is the only way for the masonry structure to regain its integrity without serious violation of the principles established by the Venice Charter.

For the whole range of irreversible interventions together with the principles applying to the repair and strengthening of ordinary structures the following two previously mentioned requirements should be taken into account:

- *compatibility* of the materials for repair and strengthening with those of the original fabric;
- *durability* of the new materials for a very long period.

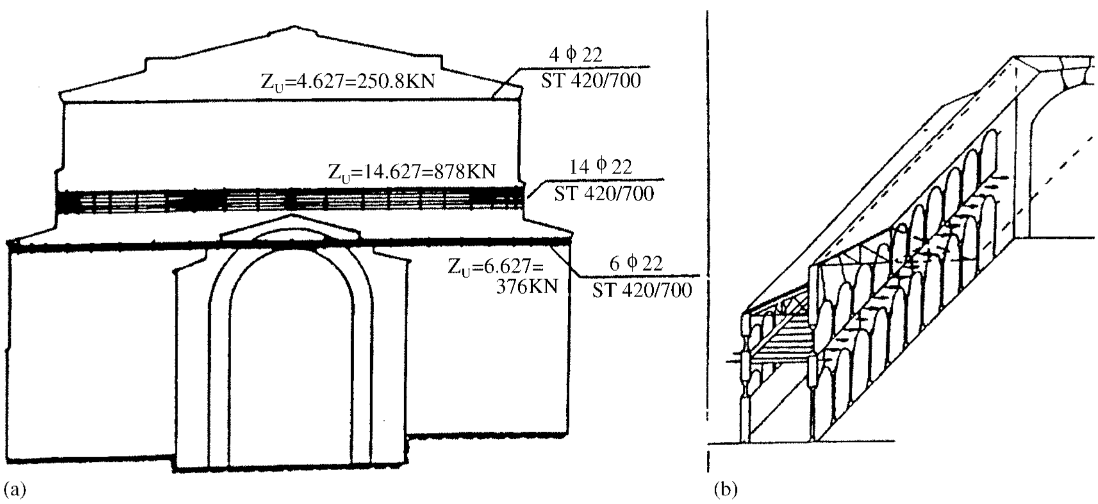

Fig. 1 Reversible interventions: (a) prestressed rings at the base of the dome of Rotunda, Thessaloniki; and (b) improvement of the diaphragm action at the arches of Acheropoieitus church, Thessaloniki.

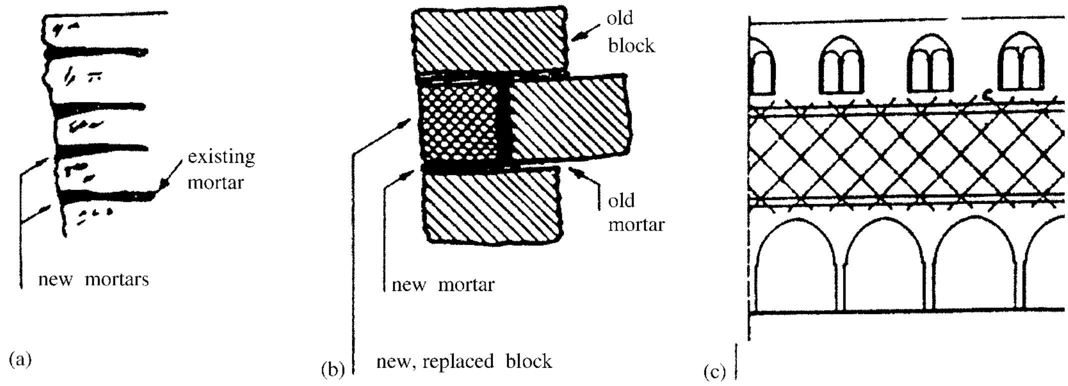

Fig. 2 Irreversible repairs: (a) deep-rejointing; (b) re-bonding; and (c) reinforcement of a colonnade (Reticolo cementato).

Table 1 Compressive strength and aggregate characteristics of old mortars

Monument	Century (AD)	Strength (N/mm^2)	Aggregate maximum size (mm)	Proportion mortar to aggregate	Fines < 0.075 mm (%)
Roman rotunda	4th	2.3	16	1:3.1	28.25
Christian rotunda	4–5th	3.7	25	1:2.5	35.40
Acheiropoieitcus	7th		16		46.69
Hagia Sophia	8th	4.5	19		24.03
Panagia Chalkeon	11th		25		20.30
St Panteleimon	12th		25		29.63
Bey Hamami	15th	1.18	06	1:2.5	45.70
Minaret of Roman rotunda	17th	1.25	30	1:2.84	38.50

The term 'compatibility' refers to the chemical, mineralogical, physical and mechanical properties of the new materials, as well as to the aesthetic harmony with the whole monument. For example, the strength, stiffness, bonding, coefficient of thermal expansion, permeability and problems of efflorescence are basic indices of compatibility. 'Durability' refers to the necessity for the lifetime of the new materials to be at least equal to that of the original fabric, and also to the necessity for preservation of compatibility between the new and the original for the same period of time. These two additional restrictions, necessitate deep knowledge of the properties of both the original and the new materials.

Materials

ORIGINAL MATERIALS

Monuments and the historical buildings may be classified in two main categories from the viewpoint of their structural form: Hinged or articulated structures with dry joints (mainly classical temples and colonnades); and masonry buildings. The main materials used for their construction were cut stone or marble, rubble, bricks, tiles, mortars, timber, iron clamps, dowels, chains, etc. From the above it is clear that the main original building materials that need to comply for co-operation with new materials *are stone, bricks, mortar.*

It is self-evident that the materials used for the construction of monumental buildings which vary owing to location, time, composition and production process, result in an unlimited number of types which by no means comply with modern standards. So, in the case of restoration of a particular monument it is necessary to study *ad hoc* the properties of its original materials. In the Laboratory of Concrete Structures, Aristotle University of Thessaloniki, Greece, an ambitious project has been launched for the creation of a database for brick and mortar used in monumental buildings in the Balkan region; some data are given in Table 1,[9–11].

The engineer responsible for the structural restoration of a monument is confronted with three main difficulties in the effort to obtain information about the chemical, physical, mineralogical and mechanical properties of the original materials:

- difficulties in extracting samples suitable for testing, making it almost impossible to apply modern standards without their radical modification[12];
- less homogeneity and uniformity than in a modern construction, so overall strengths will be less predictably related to the unit strengths of the constituent materials;
- difficulties in assessing the mechanical properties of the original masonry through the relevant

properties of the constituent materials (stone, brick, mortar). On this last issue detailed reference will be made below[13].

MATERIALS FOR REPAIR AND STRENGTHENING

The best way to ensure compatibility and durability of materials for repair and strengthening is the use of traditional materials of the same composition as the original. However, this is not always possible for various reasons[14]:

- difficulties arise in the recomposition of the traditional material due to inability of detailed analysis of the original (additives, etc.);
- the requirement for the new material to gain the strength of the original in a relatively short time does not allow the choice of the same composition;
- the requirement for grouts to have high fluidity results in a much lower strength than the original mortar of the same composition;
- there is often a need for the parallel use of modern materials (e.g. stainless steel) as stitches to ensure the desired interaction along planes of fracture between old material and grouts through shear, friction, etc.[15].

Non-metallic materials

From the materials of irreversible interventions the most important are: stone and marble, brick, mortar and grout, concrete. The composition of compatible mortars and grouts for restoration presents the biggest difficulty. Common types of mortars and grouts for restoration are: Portland cement; lime cement; pozzolana; and epoxy resins. Of these pozzolana-based mortars and grouts may be considered the most appropriate ones for the restoration of Byzantine and Islamic monuments in the Mediterranean region[14].

Metallic materials

Where high tensile strength or prestressing forces are required, steel is usually necessary, in spite of its liability to corrosion; alternatives such as titanium would be too expensive. On the other hand, modern materials, such as organic or inorganic fiber composite cables or sheets (FRPs) constitute a promising new approach to the problem. The negative consequences of steel corrosion may be summarized as:

- reduction of the strength of the corroded bars due to their cross-section reduction;
- cracking of the building elements due to the swelling of corroded steel;
- loss of bond action;
- appearance of rust stains on the building.

The most usual types of metallic materials for structural restoration are given below in order of their corrosion resistance and cost:

- coated steels (zinc, lead or resin coating);
- stainless steels—the most suitable for building construction are the austenetic steels of chromium, nickel and molybdenum (Ch–Ni–No)[3].
- titanium bars are applied where the value of the monument does not allow any risk of future corrosion. Titanium is a relatively light metal and its most important feature is its exceptionally good corrosion resistance. This material has been used extensively for the structural restoration of the Acropolis and, National Library in Athens, and the Acheiropoieitos in Thessaloniki, among others.

The structural restoration procedure

As previously mentioned, the materials, techniques and design procedures to be employed are strongly related to the intervention scheme, the formation of which constitutes the essence of the structural restoration procedure. Accordingly, the following paragraphs outline the successive steps in this procedure, with some comments on its main issues. In closing, it should be noted that the archaeological and architectural surveying of the successive phases of the monument or historical building must precede the structural restoration design activities, or at least they must run in parallel.

STEPS IN THE PROCEDURE

Temporary shoring

This is a separate step in the restoration procedure, particularly when restoration is decided upon after a strong earthquake, which has caused damage threatening partial or total collapse. By this means, sufficient time is gained for a detailed approach to the problem. This step is usually combined with the scaffolding necessary for the following investigations and works.

In-situ investigations

These usually include the following activities[16, 17]:

- geometric and constructional survey;
- survey of the pathology of the structure;
- *in situ* non-destructive tests (NDT), e.g. hammer testing, ultrasonic measurements, ambient vibration measurements;
- follow-up of changes in cracks, inclinations, etc. with time.
- *in situ* soil investigations (boreholes, excavations near the foundations, etc.);

Laboratory tests

These usually include the following activities:

- determination of chemical and mineralogical properties of the original materials;
- determination of mechanical properties of the original materials;

- ensuring composition of mortars and grouts compatible to the original ones;
- soil tests on samples taken from the boreholes;
- model tests (e.g. scaled walls or piers).

Analysis and design of the original structure
The analysis and design of a monumental building before the intervention is a very important step and includes as prerequisites the following actions:

- determination of the mechanical properties of masonry and other compound elements (modulus of elasticity, $\sigma-\varepsilon$ curves, $\sigma-\tau$ curves, $\sigma_1-\sigma_2$ curves, etc.);
- determination of the dynamic characteristics of the building (fundamental period T, etc.);
- determination of the ductility behaviour factor (q-factor) of the building;
- determination of the scaled design spectrum or scaled accelerograms for use in the analysis.

For the analysis of the structural system various approaches may be used. The most common are the following:

- elastic–static for frame or shell elements;
- elastic–dynamic for frame elements;
- static–inelastic analysis by a step-by-step method for determination of the collapse mechanism and loads (pushover analysis);
- static–inelastic analysis with upper- and lower-bound theorems, for determination of the collapse loads.

For the design of the cross-sections the $\sigma - \tau$ curves or $\sigma_1 - \sigma_2$ curves must be used.

Assessment of the residual resistance of the structure
Taking into account the pathology of the structure, the time history of cracks and inclinations, the soil investigations and mainly the results of the analysis and design of the original structure, an estimate of the residual resistance of the original structure is made. This estimate, carried out by the structural engineer in charge, is crucial for decision-making on the type and degree of the intervention scheme for the structural restoration.

Restoration scheme
Formation of the restoration scheme constitutes the core of the whole procedure and it is the output of an interrelated approach from the structural, architectural and archaeological points of view[18]. Usually, the structural engineer in charge formulates various alternatives fulfilling the safety requirements based on a global estimate of the *in-situ*, laboratory and analytical investigations. After exhaustive discussions with the other co-operating parties to the restoration, the final solution is formed.

Analysis and design of the modified structure
The modified structural system of a monumental building must be analysed and re-dimensioned by the procedure already presented.

Drawings, descriptions and specifications
The whole design is completed with general drawings, detailing drawings, technical descriptions and technical specifications, all necessary for the works on-site.

COMMENTS
From the procedural steps presented above, it may be concluded that analysis and design play a vital role at two stages in the structural restoration:

- to estimate the residual resistance (strength–rigidity–ductility) of the original structure, which is crucial information for a decision on the type and degree of restoration.
- to reanalyse and redesign the modified structure—necessary for safety verification of the restored building.

Analysis and design of the original structure

It might be said that the analysis and design in structural restoration is nothing more than an application of the theory of structures to monumental buildings. In this respect the problems confronted in the assessment of the residual resistance of the original structure and the verification of the safety level of the restored one can be easily solved by implementation of routine methods in use in contemporary buildings.

This is only partly true. The problem of restoration differs radically from the problem of repair and strengthening of ordinary buildings, as the aim of the restoration according to the Venice Charter[1] is to preserve and reveal the aesthetic and historical values of the monument or historical building.

In this respect and taking into account the principles presented at the outset, a very strict framework is created for the analysis and design. The structural engineer, working with unreliable and uncodified materials of the original texture and questionable information on the past history of the structure, is obliged to analyse it, and to try to improve its structural capacity with strictly limited means compared with those available for an ordinary building. In this respect the analysis and design in structural restoration is a real challenge. In the following discussion some of the main issues will be briefly presented.

PRELIMINARY INFORMATION
The main items of preliminary information necessary for the analysis and design which cause uncertainties are:

- the mechanical properties of the masonry;
- the behaviour factor (q-factor) of the structure;

- the choice of scaled acceleration response spectrum or scaled accelerograms;
- $M-\theta$ diagrams of the basic structural elements or the stress–strain tensors relationship in the inelastic state.

The mechanical properties of the masonry

Assessment of the mechanical properties of the original masonry—strengths, modulus of elasticity and Poisson ratio—necessary for the analysis and design, is a very difficult task, including many uncertainties, as the usual procedure to obtain these values is to use various empirical formulae where the geometry of the masonry and the unit strengths of the constituent materials (brick–mortar) are interrelated. All these formulae are based on test results of codified masonry types and therefore their results are unreliable for massive Roman, Byzantine and Islamic walls. The procedure of extracting full-scale specimens from the masonry is too destructive and therefore not allowable for a monument. Recently extensive research has been carried out in this direction, either by means of partially destructive methods[19] or by means of FEM[13] with microelements of mortar and bricks (Fig. 3). However, even these recent studies cannot deal with the problem of massive walls which present a structure with two external walls and a core of rubble.

The behaviour factor (q-factor)

The behaviour factor necessary for a quasi-static or dynamic–elastic analysis of the structure cannot be taken from the codes of practice for masonry structures. Therefore, an inelastic–static approach for the main elements of the structure (piers, walls) should be carried out (pushover analysis) for determination of the $H-\delta$ curve and the relevant ductility behaviour factor (Fig. 4,[3,6]).

The scaled acceleration response spectra

Bearing in mind that the recorded information on seismic actions covers a period of only 50 years or so[20], it is difficult to accept that this information can be used with high reliability for a monument which has survived for centuries and for which the future life perspectives are limited. Another crucial point is the Peak Ground Acceleration (PGA) that should be adopted for the scaling of the spectra or accelerograms. If the aseismic code provisions is adopted the return period of occurrence is unacceptably short. If a longer return period is adopted the (PGA) adopted would lead to unacceptable structural interventions. It seems reasonable to base the validation of this scaling on the strength of crucial elements, in combination with their behaviour during earthquakes in the past[3].

M–θ diagrams

If inelastic analysis is adopted, additional complicated and often unreliable information on mechanical properties has to be introduced. Even for the simple case of frame models under static loading, the $M-\theta$ diagrams of all basic elements should be determined. For masonry, the preparation of such information is not an easy task, particularly if bending combined with shear deformation has to be taken into account[21]. The problem becomes almost insuperable in the case of surface or solid elements where the stress–strain tensor relation of orthotropic–inelastic material is needed. It is self-evident that additional uncertainties interfere when the descending branch of the stress–strain curve is needed for inelastic–dynamic analyses.

STRUCTURAL SYSTEMS: METHODS OF ANALYSIS AND DESIGN

The ideal approach to the problem would be the analytical calculation of the time history inelastic response of the monument for dead loads and for soil excitation, by a series of probable accelerograms, using the finite element method. However, such an approach to the problem even today seems, for many reasons that are mentioned below, to be unrealistic:

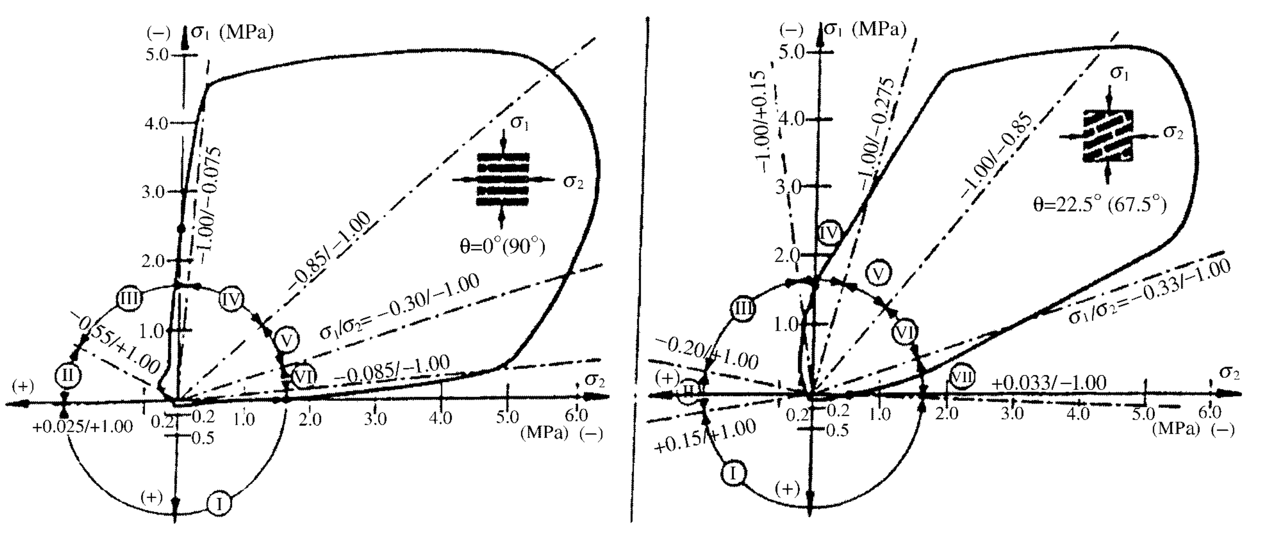

Fig. 3 Analytically determined failure envelops of Roman Masonry (Rotunda of Thessaloniki).

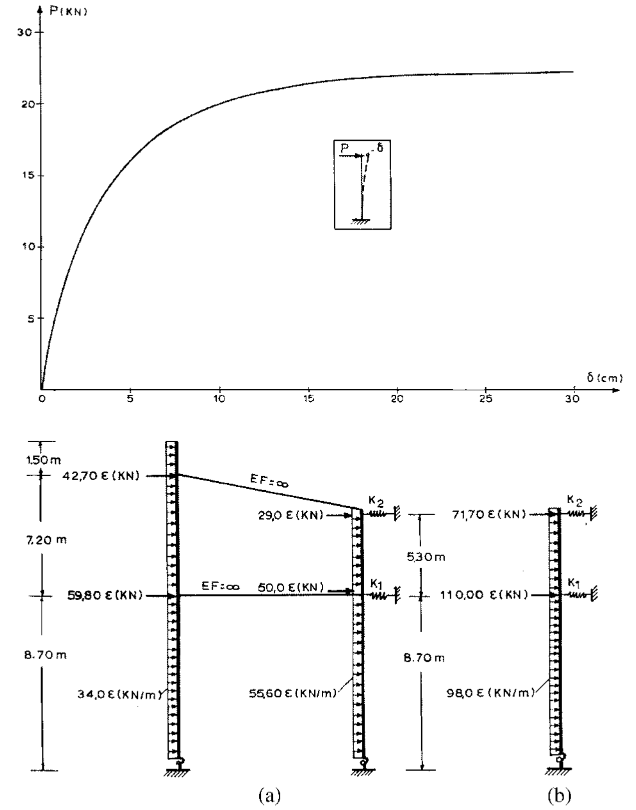

Fig. 4 Push-over analysis of Acheropoieitus church, Thessaloniki, Greece. Structural model and $P-\delta$ curve.

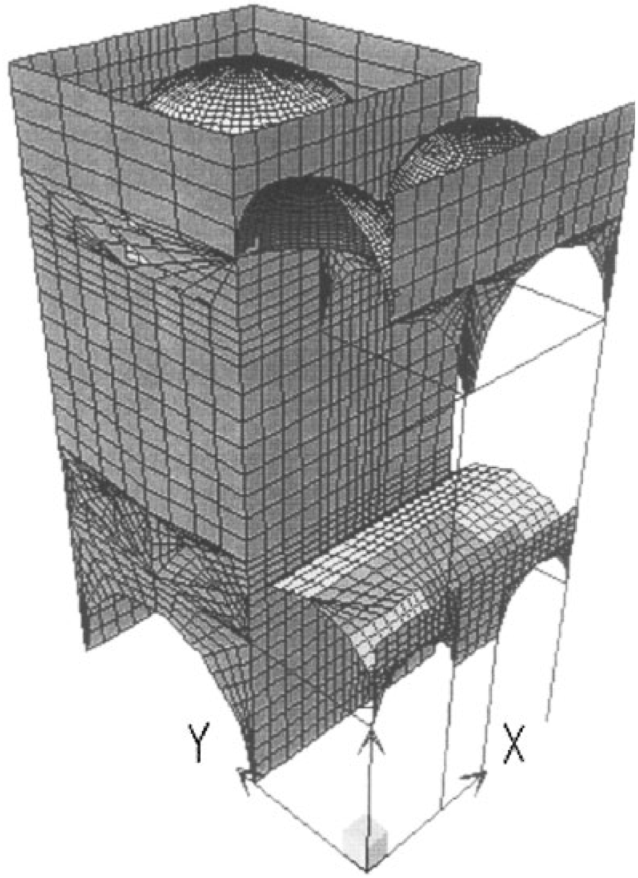

Fig. 5 Discretization of a unit of Saint Dionysius Monastery at Olympus maintain, for a FEM elastic dynamic analysis.

- the solid state discretization of complicated, huge, massive structures is very difficult[22];
- reliable stress–strain inelastic triaxial relations cannot be easily adopted, as the masonry is a unilateral, orthotropic structure with varying orthotropy and material properties, almost from point to point. Additionally, the descending branch in the stress–strain constitutive law, necessary for cycling loadings, cannot be estimated in a justifiable way;
- the adoption of a reliable strength envelope varying from area to area of the structure cannot be supported by experimental evidence; moreover, when the independent variables are not only the stresses σ_1, σ_2, σ_3 but also the direction cosines of the masonry orthotropy (direction of the bed joints)[23];
- the loading path, which plays an important role in inelastic analysis, cannot be easily guessed for a monument with a history of many centuries. More over the long term effects of loading cannot be easily taken into account[24];
- the existing cracks due to foundation settlements, various restraints or accidental actions in the past (i.e. earthquakes) cannot be easily taken into account in the analysis of the existing structure, and are even more difficult to reproduce analytically in the successive loading steps up to failure;
- last, but not least, it is very difficult to adopt reliable accelerograms for the dynamic analysis of the monument when the existing information on this matter is limited to the last 40–50 years.

Taking all these uncertainties into account it appears fairly impractical to try a sophisticated analysis by modern general-purpose FEM programs or even problem-oriented FEM programs. In fact, when so many parameters of the problem are uncertain and the results are so sensitive and highly dependent on these parameters, these results may not be trustworthy[5].

On the other hand, an elastic–static or dynamic analysis of frame or shell simulated structures, which constitutes the most simplified approach to the problem, must be considered as a method of limited reliability, owing to the low tensile strength and the orthotropy of the masonry, together with the uncertainties of the mechanical properties of the original materials, the existing cracks and settlements. Such an analysis must be considered useful only for the verification of the existing crack pattern in the service state (Fig. 5,[6]).

Bearing all these in mind, it is the author's opinion that, for the residual load bearing capacity of a monument to be determined the procedure below should be followed[25]:

- in principle, the necessity for structural analysis of a monument that has survived for centuries arises

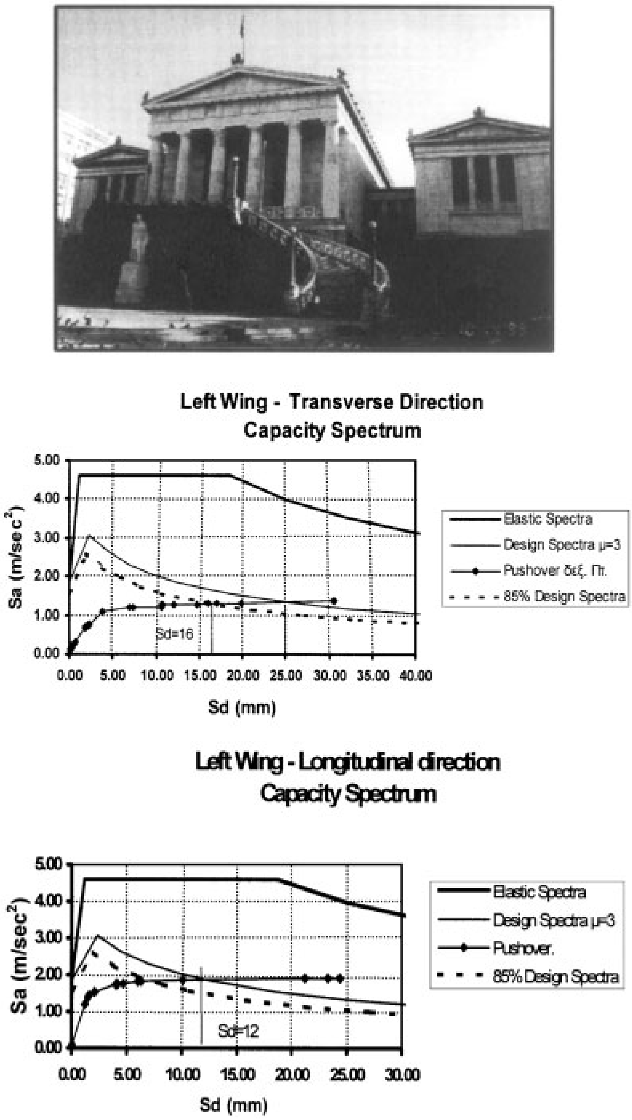

Fig. 6 Case Study-National Library in Athens. General view of the complex; pushover analysis in transverse direction; pushover analysis in longitudinal direction.

only when failure symptoms appear on its structure. (detectable deformations and settlements, etc.). There is no better index of structural efficiency for a monument than its survival for centuries without structural defects;

- so, with the crack pattern and the deformations of the structure as a guide, we determine the expected failure mechanism, either with the step-by-step method of inelastic analysis (pushover analysis)[26] or the theorems of plasticity for upper and lower bounds[3,27]. The structure in this case is usually simulated by a frame system[28] or preferably by a shell FEM system[29];
- for this failure mechanism we determine the ultimate load and displacement of the structure. This output constitutes a sound basis for the performance-based design[30,31] of the monument (Fig. 6);
- the extrapolation of the results of elastic or even inelastic analysis up to ultimate state should not be considered as reliable if the resulting failure mechanism does not comply with the existing crack and deformation pattern of the monument;
- special attention should be given to the dynamic analysis of articulated monuments. The possibility of rocking and sliding of the individual members at their contact joints provides very difficult analytical problems for the analysis itself and for the evaluation of the results[32];
- last, but not least, special attention should be given to the choice of the *partial safety factors* for materials and loads, particularly in the case of buildings that will be given over to use by many people (churches, public buildings, etc.). For example, the partial safety factors for dead loads and strength of original materials might be chosen lower than those codified for new buildings, since dead loads and original materials are already embodied to the structure and therefore fixed. On the other hand, for seismic actions the considerations presented earlier in this paper should be taken into account[25].

Reanalysis and redesign of the modified structure

Before the reanalysis and redesign of the structure, one of the alternative restoration schemes is adopted. This scheme is reanalysed and redesigned, following the same methodologies as these presented in the preceding section. However, the choice of the restoration scheme should take into account the following considerations.

From the study of a very broad range of monuments and historical buildings it is concluded that one of the most important causes of damage to their structural system in areas of high seismicity is earthquake action. It may be said that these buildings, being exposed every now and then for centuries to strong seismic actions, have been subjected to a kind of *natural selection*, so that only those which were properly designed and constructed have survived[3].

Consequently, in the case of structural restoration *the preservation of the original structural system or the proper strengthening of its weak elements must be one of the basic concepts of the intervention*. Nothing can guarantee that a strongly modified structural system will have a better chance than the original one of surviving to in the following centuries.

On the basis of the preceding remarks, it may be said that the seismic and dynamic analysis of a monument for a proposed intervention arises only when the building presents detectable failure symptoms (cracks, deviations from the vertical, settlements of the foundation or continuous worsening of the above symptoms).

With all these in mind the intervention scheme is decided. It usually includes two types of intervention[33]: *local* and *general interventions.*

The first type refers to interventions that improve the local strength or integrity of the structural members—deep rejoints, grouting, stitching of walls with prestressed rebars, etc. The second type refers to interventions that improve the overall structural behaviour of the building—ties at the springings of arches, rings at the base of domes, external buttresses, improvement of the stiffness of existing diaphragms, etc. This second type of intervention calls for the reanalysis and redesign of the structure.

Conclusions

In areas of high seismic hazard, earthquakes are the predominant cause of damage or collapse of monuments and historical buildings. For centuries these buildings have periodically suffered strong seismic actions and have undergone a kind of natural selection, so that only those that were well designed and constructed have survived.

Consequently, when structural interventions are made, the original structural system should in principle be kept unchanged. At most, only local repairs or improvement of the original structural system should be accepted. No one is in a position to guarantee that a strongly modified structural system will have a better chance than the original of surviving into the following centuries.

In order to estimate the load-bearing capacity of a monument from dead or seismic loads and to make decisions about possible interventions, a complicated restoration procedure is followed. This procedure begins with temporary shoring and installation of scaffolding for access to the monument, and continues with *in-situ* measurements and investigations, laboratory tests, and rigorous structural analyses.

In the event that any structural intervention is decided upon, it should be kept in mind that the aim of the restoration is to preserve and reveal the aesthetic and historical value of the monument, and is based on respect for the original materials and authentic documents. This imposes on the specialists responsible for the restoration a duty to consider what limitations these considerations place on the choice of techniques and materials for repair and strengthening.

The key to the choice of materials and techniques is the classification of methods into two main categories: reversible and irreversible. Materials used in reversible interventions usually impose very few restrictions. In contrast, materials used in irreversible interventions impose the following two additional restrictions: compatibility of the new materials with the original ones; and very-long-term durability of the new materials. These restrictions necessitate a thorough knowledge of the properties of the original materials so that they can be used as a guide to the choice of materials for repair and strengthening. It is generally accepted that the best way to satisfy the requirements for compatibility and durability is to choose 'traditional materials' for restoration.

Structural restoration is a highly specialized operation, one that calls for the collaboration of specialists in many scientific disciplines such as archaeology, architecture, surveying, structural engineering and chemical engineering, strongly supported by computational methods and well-equipped laboratories.

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