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TECHNIQUES & MATERIALS FOR STRUCTURAL RESTORATION

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ABSTRACT

Techniques and materials in use for the structural restoration of historical buildings and monuments damaged by earthquakes are presented on a concept basis and in relation to the restoration principles as they are stated in the Venice Charter. In parallel, brief comments are given on the procedure followed in the structural restoration for the formation of the intervention scheme.

KEYWORDS

Restoration techniques; restoration materials; restoration procedure; structural restoration; monuments and earthquakes; monuments and seismic protection; historical buildings and earthquakes.

INTRODUCTION

The task of this paper is to outline the techniques and the materials 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 (UNDP/UNIDO, 1984).

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 at fulfilment of the main task. So, the aim of the restoration according to the Venice Charter (UNDP/UNIDO, 1984) is to *preserve* and *reveal* the aesthetic and historical values of the monument or historical building.

Particularly for the structural restoration, the basic principles that should be taken into consideration may be resumed as follows:

- Respect for original material and authentic documents.
- Respect to the valid contributions of all periods to the building.
- Replacements of missing parts must intergrate 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 are *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 which may cause damage.

TECHNIQUES FOR STRUCTURAL RESTORATION

Introductory Remarks

Keeping in mind what was already presented above and what is included in Article 10 of the Venice Charter, it is concluded that the Intervening Procedure to a monument is an action of high complexity and requires special techniques and materials 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 the Techniques

The restoration techniques may be classified in two categories (Penelis et al., 1989a)
- Reversible
- Irreversible.

Generally speaking reversible actions are preferable for the following reasons:
- In the case that they will be proven inefficient or of low durability to time they can be replaced without damage to the original fabric.
- In the case that in the future better techniques or materials are developed they can be replaced easily.
- The artistic or historical evidence is not falsified at all.

The following techniques may be classified in the category of reversible actions :
- External buttresses.
- Ties at the springings of arches.
- Rings at the base of domes (Fig. 1a), (Penelis et al., 1990).
- Prestressed unbonded stitches.
- Anastylosis of stone or marble monuments with dry joints.
- External ties.
- Internal steel curbs for confinement.
- Improvement of the strength, stiffness and ductility of existing diaphragms (Fig. 1b) e.t.c.

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

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

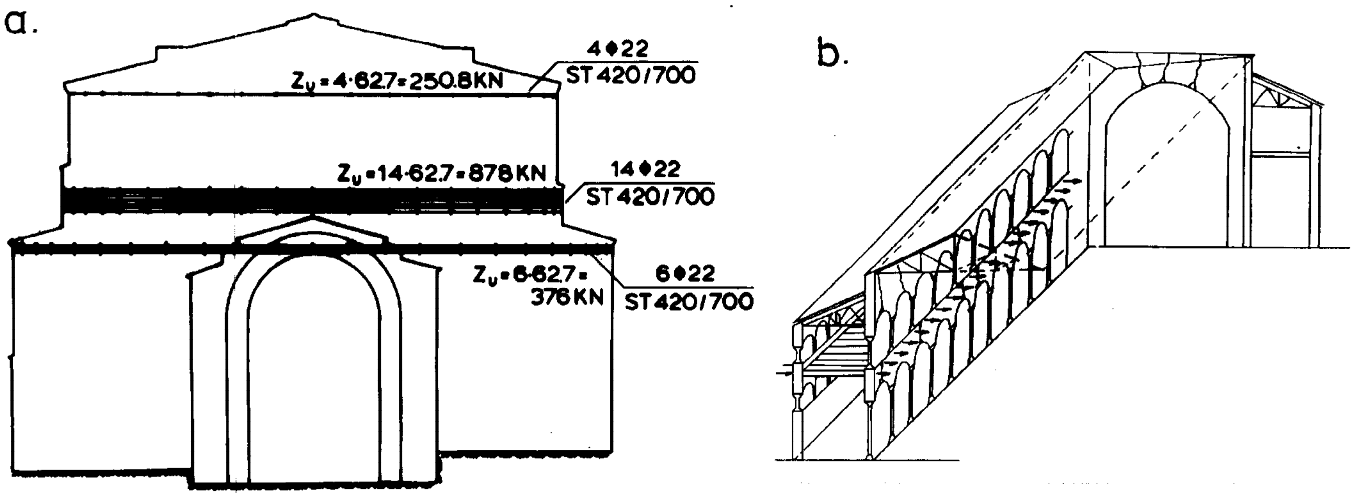

Fig. 1 Reversible interventions
(a) Prestressed rings at the base of the dome of Rotunda, Thessaloniki
(b) Improvement of the diaphragm action at the arches of Acheropoieitus church, Thessaloniki

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

- Groutings
- 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) (Lizzi, 1989).
- Interconnections of marble or stone parts with bonded dowels.
- Skins of reinforced concrete on masonry walls or upper side of vaults.
- Strengthening of foundations e.t.c.

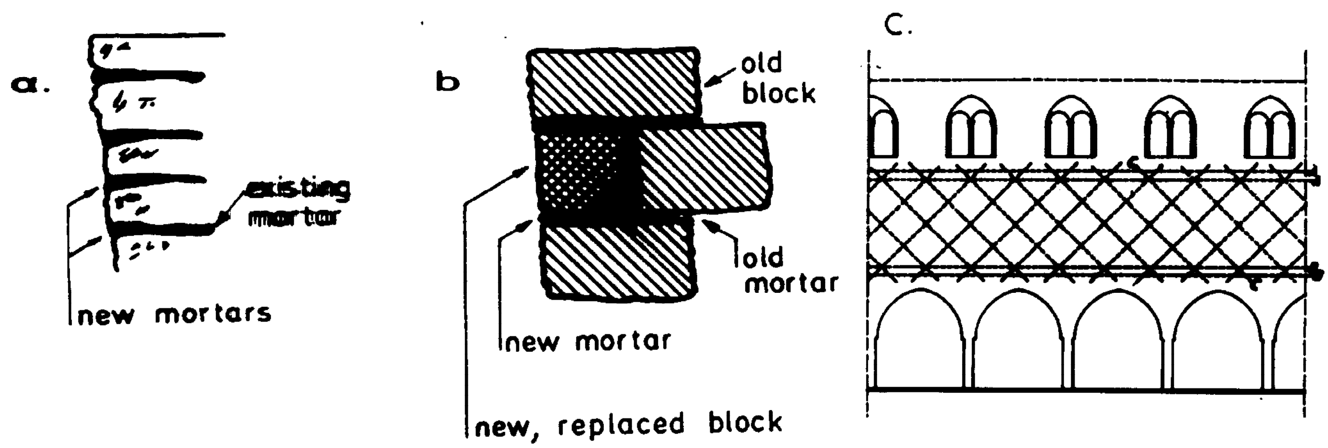

Fig. 2. Irreversible repairs. (a) Deep-rejointing, (b) Re-bonding,
(c) The reinforcement of a colonnade (Reticolo cementato)

From the above mentioned techniques the grouting, bonding-in of new bricks across cracks, deep rejointing 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 any serious violation of the principles of actions 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 of time.

The term "compatibility" is refered to the chemical, mineralogical, physical and mechanical properties of the new materials. In addition it is refered to aesthetic harmony with the whole monument. For example, the strength, the stiffness, the bonding, the coefficient of thermal expansion, the permeability and the problem of efflorescence are basic points of reference of the term "compatibility".

With the term "durability" reference is made 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 the compatibility between the new and the original for the same period of time.

These two additional restrictions, that is, the *compatibility* and the *durability* necessitate the deep knowledge of the properties of the original materials on one side and of the new ones on the other.

MATERIALS FOR REPAIR AND STRENGTHENING

The Original Materials

The monuments and the historical buildings may be classified in two main categories from the viewpoint of their structural form :

i. Hinged or articulated structures with dry joints (mainly classical temples and colonnades).
ii. Masonry buildings.

The main materials used for their construction were :

- cut stone or marble, rubble, bricks, tiles, mortars, timber, iron clamps, dowels, chains e.t.c.

From the above it is clear that the main original building materials called for co-operation with the new ones are the stones, the bricks and the mortars.

It is self evident that the materials used for the construction of monumental buildings which vary due to location, time, composition and production process, result in an unlimited number of types which by no means comply with modern standards. So, in 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 data base for bricks and mortars used in monumental buildings in the Balkan region, Table 1, (Karaveziroglou et al., 1995).

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

- There are difficulties in extracting samples suitable for testing so, it is almost impossible to apply modern standards without their radical modification.
- There is less homogeneity and uniformity comparing to a modern construction so that overall strengths will be less predictable related to the unit strengths of the constituent materials.
- There is considerable variation in the properties of the constituent materials themselves.

Table 1. Compressive strength and aggregate characteristics of old mortars

Monument	Century	Strength (N/mm^2)	Aggregate max size (mm)	Proportion mortar to aggregate	Fines <0.075mm (%)
Rotunda Roman	4^{th} AD	2.3	16	1:3.1	28.25
Rotunda Christian	$4\text{-}5^{th}$ AD	3.7	25	1:2.5	35.40
Acheropoieitus	7^{th} AD	-	16	-	46.69
Hagia Sophia	8^{th} AD	4.5	19	-	24.03
Panagia Chalkeon	11^{th} AD	-	25	-	20.30
St. Panteleimon	12^{th} AD	-	25	-	29.63
Bey Hamami	15^{th} AD	1.18	6	1:2.5	45.70
Minaret of Rotunda	17^{th} AD	1.25	30	1:2.84	38.50

At this point, it should be noted that the assessment of the mechanical properties of the original masonry, that is 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 formulas where the geometry of the masonry and the unit strengths of the constituent materials (bricks-mortar) are interrelated. 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 (Berger, 1989) or by means of F.E.M. (Stavrakakis et al., 1995) using micro elements of mortar and bricks. It is the authors opinion that the latter is the most promising for the determination of the failure envelope (σ_1-σ_2) and the constitutive law σ-ε of the original masonries (Fig. 3).

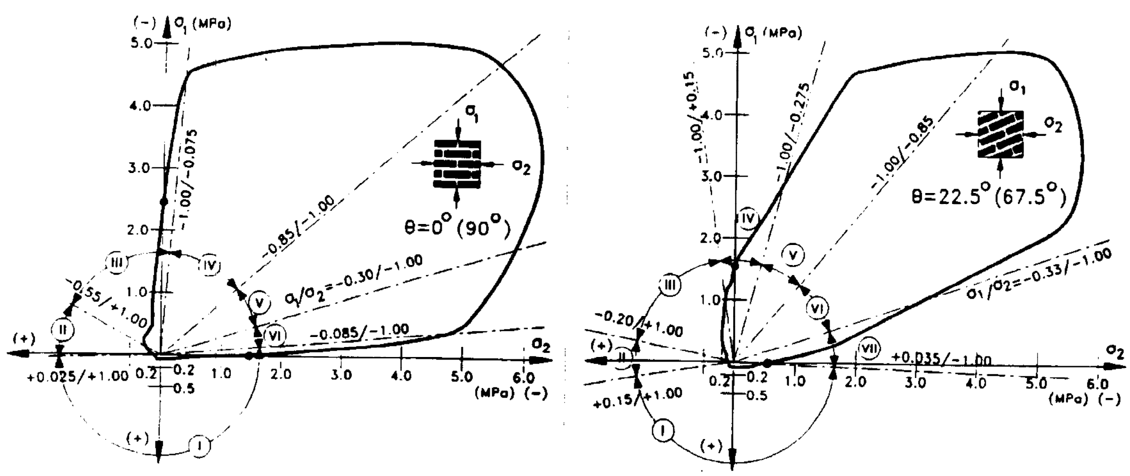

Fig. 3. Analytically determined failure envelopes of Roman masonry (Rotunda of Thessaloniki)

The Materials for Repair and Strengthening

Introductory Remarks. 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 procedure is not always possible for various reasons.

Difficulties arise in the recomposition of the traditional material due to inability of detailed analysis of the original (additives e.t.c.).
- 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 in the case of the same composition.
- Many times there is a need for the parallel use of modern materials (e.g. stainless steel) as stitches to ensure the desired interaction along planes of fracture (Tassios, 1986).

Non-metallic Materials. From the materials of irreversible interventions the most important are :
- Stone and Marble, Bricks, Mortars and Grouts, Concrete.

The composition of mortars and grouts for restoration activities compatible to the originals presents biggest difficulty. Common types of mortars and grouts for restoration are given below :
- Portland cement mortars and grouts
- Lime-cement mortars and grouts
- Pozzolanic mortars and grouts
- Epoxy resin mortars and grouts.

From the above the pozzolanic mortars and grouts may be characterized as having of high efficiency and compatibility for the restoration of Roman Byzantine and Islamic monuments around Mediterranean sea (Penelis et al., 1986).

Metallic Materials. Where high tensile high strength or prestressing forces are required, steel must usually be used in spite of its liability to corrosion; alternatives, as for example titanium would be too expensive. On the other hand modern materials such as organic or inorganic fiber composite cables constitute a new promissing approach to the problem. The negative consequences of steel corrosion may be summarised as follows :
- 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 elements in use for the structural restoration are given below in sequence to their corrosion of resistance and cost :
- *Coated steels* with zinc coating, lead coating, resin coating.
- *Stainless steels*. The most suitable for building construction are the austenetic steels with chromium, nicelium and molybdenum (Ch-Ni-No type).
- *Titanium bars*. They are applied where the value of the monument does not allow any risk of future corrosion. It is a relatively light metal and its most important feature is its exceptionally good corrosion resistance.

THE PROCEDURE OF THE STRUCTURAL RESTORATION

Introductory Remarks

As previously mentioned the materials and techniques to be employed are strongly related to the intervention scheme the formation of which constitutes the main action of the structural restoration procedure. So, it was thought interesting to include here some comments on this procedure.

Comments on the Procedure

From the study of a very broad range of monuments and historical buildings it is concluded that one of the most important cause of damage to their structural system in areas of high seismicity is the 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 (Penelis et al., 1990).

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. Nobody and by no means could guarantee that a modified structural system will have a better chance than the original one to survive in the following centuries.

Based on the preceding remarks it may be said that the static and dynamic analysis of a monument for a possible intervention arises only when the building presents detectable failure symptoms that is :
- cracks, deviations from the vertical, settlements of the foundation or continuous worsening of the above symptoms.

There is not a better index of structural efficiency for a monument than the fact of its survival for centuries without structural defects. Particularly for the structural analysis of a monumental building the following comments may be considered of interest.

- Having the crack pattern and the deformations of the structure as a guide the expected failure mechanism is determined either using the step-by-step method of inelastic analysis or the upper and lower bound theorems of plasticity.
- For this failure mechanism the ultimate load is determined. The ratio of the ultimate to service load constitutes a reliable index of the level of overall safety of the structure.
- The elastic or inelastic analysis for the service loads provides one of the probable stress states of the monument, useful for the verification of the crack pattern in this state.
- -- The extrapolation of the results of elastic for even inelastic analysis up to the ultimate state should not be considered as reliable if the resulting failure mechanism would not comply with the existing crack and deformation pattern.
- Special attention should be given to the partial safety coefficients for materials and loads particularly in the case of buildings that will be given to the use of many people (i.e. churches, public buildings e.t.c.).

From the above, it can be concluded that for the estimation of the residual resistance of a historical building to gravity loads and seismic actions and for the decision making on the proper intervention scheme, it is necessary to have a deep knowledge of the structural system, the properties of the original materials, the crack and deformation pattern and their changes in time, the structural response to gravity and seismic loads , the seismic hazard of the region.

CONCLUSIONS

In areas of high seismic risk, earthquakes are the predominant cause of damage to and 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.

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 of repair and strengthening.

The key to the choice of materials and techniques is the classification of the second 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 for 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 specialised operation, one that calls for the collaboration of specialists in many scientific disciplines such as archaeology, architecture, survey engineering, structural engineering and chemical engineering, strongly supported by computational methods and well-equipped laboratories.

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