STRUCTURAL RESTORATION OF HISTORICAL MONUMENTS. SPECIFIC EXAMPLES FROM GREEK PRACTICE

Anastasiadis S. Anthimos
Dr. Structural Engineer. Litohorou 19, T.K 546.38 Thessaloniki, Greece

Abstract
Firstly the paper presents the structural concept of repair and strengthening of historical monuments, according to Venice Charter, discussing the general philosophy of interventions, analysis problems, design methodologies, techniques and materials used. Secondly, describes some specific examples of structural restoration of ancient and Byzantine monuments damaged due to man-made or natural loading, in this way introducing in a concise mode all the problems discussed earlier.

Keywords: structural concept, restoration methodology, analysis and design, restoration measures, techniques and materials, case studies on ancient and Byzantine Greek monuments.

1. INTRODUCTION
Following the evolution of the human culture, it is easy observed that one of the main activities of human being is to construct. Wherever a high level of culture is developed also specific structural materials, structural typologies and constructive techniques were developed as a trademark of this period. Consequently, a unique structural heritage was formed after 2500 years of life, which with passing of time, as is normally, has been deteriorated or damaged due to interior (e.g. use) or exterior (e.g. earthquakes, fires, e.t.c.) actions. Certainly, this architectural and structural originality should be conserved not only for historical, cultural, touristic reasons but even demonstrating the way of thinking of specific periods.

An early restoration action was marked when Alexander the Great had gave an order to someone called Aristovoulos to rehabilitate some deteriorated parts from the grave of Kyrous at Pasargades, of course ignoring the importance of conservation. The first concrete recognition for the restoration of historic monuments was adopted at the First International Congress of Architects and Technicians of Historic Monuments, in Athens 1931. Seven main resolutions were made called `Carta del Restauro``(Tab.1), defining basic principles for the first time. The Athens Charter of 1931 contributed towards the development of an extensive international movement. After 30 years of studies an enlargement at Second International Congress, which met in Venice, 1964, was made with the approval of a new more comprehensive document having sixteen articles including practical directions in order to conserve and restore historical monuments. In table 2 specific articles important in structural intervention are presented. Acting in the spirit of Venice Charter, taking into account the international recommendations as well as the process of European unification a new document was created, the Charter of Krakow 2000, defining the principles for conservation and restoration of build heritage. The entire aforementioned documents act as guidelines in structural restoration. The three Charters, as a pioneer work, recommend the
European way of thinking in monumental interventions, efficient for all restoration projects [8]. For the first should be noted that the restoration process is an action of high complexity with a multidisciplinary consideration needing the participation of archeologists, architects, surveyors, geologists, and structural engineers.

Table 1. The main resolutions of Athens Charter.

<table>
<thead>
<tr>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. International organizations for Restoration on operational and advisory levels are to be established.</td>
</tr>
<tr>
<td>2. Proposed Restoration projects are to be subjected to knowledgeable criticism to prevent mistakes that will cause loss of character and historical values to the structures.</td>
</tr>
<tr>
<td>3. Problems of preservation of historic sites are to be solved by legislation at national level for all countries.</td>
</tr>
<tr>
<td>4. Excavated sites, which are not subject to immediate restoration, should be reburied for protection.</td>
</tr>
<tr>
<td>5. Modern techniques and materials may be used in restoration work.</td>
</tr>
<tr>
<td>6. Historical sites are to be given strict custodial protection.</td>
</tr>
<tr>
<td>7. Attention should be given to the protection of areas surrounding historic sites.</td>
</tr>
</tbody>
</table>

Table 2. Fundamental restoration principles according to Venice Charter.

<table>
<thead>
<tr>
<th>Article</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARTICLE 6</td>
<td>The conservation of a monument implies preserving a setting which is not out of scale. Wherever the traditional setting exists, it must be kept. No new construction, demolition or modification, which would alter the relations of mass and color, must be allowed.</td>
</tr>
<tr>
<td>ARTICLE 9</td>
<td>The process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp. The restoration in any case must be preceded and followed by an archaeological and historical study of the monument.</td>
</tr>
<tr>
<td>ARTICLE 10</td>
<td>Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.</td>
</tr>
<tr>
<td>ARTICLE 11</td>
<td>The valid contributions of all periods to the building of a monument must be respected, since unity of style is not the aim of a restoration. When a building includes the superimposed work of different periods, the revealing of the underlying state can only be justified in exceptional circumstances and when what is removed is of little interest and the material which is brought to light is of great historical, archaeological or aesthetic value, and its state of preservation good enough to justify the action. Evaluation of the importance of the elements involved and the decision as to what may be destroyed cannot rest solely on the individual in charge of the work.</td>
</tr>
<tr>
<td>ARTICLE 12</td>
<td>Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence.</td>
</tr>
</tbody>
</table>
According to those it is very important to give and clarify the basic definitions of monument, conservation, preservation, restoration, renovation, reconstruction.

- **Monument** is any structure or group of buildings with the following attributes:
  i) Historical value associated with important historical events
  ii) Socio-cultural value depicting worth and experiences.
  iii) Artistic or architectural value bearing local or interrelation between local and foreign influences of a certain period style.
  iv) Unique and distinct characteristics.

- **Intervention** is a multi disciplinary means of safeguarding the country’s historico-cultural heritage to suitable adapt it to the needs of the society. Generally, the conservation action is the complex of attitudes of a community that contributes to making the heritage and its monument endure.

- **Conservation** is the maintaining or cleaning of a monumental structure in order to extend its lifespan.

- **Restoration** is the methodological and controlled repair and strengthening of a structure in order to conserve its original state and to prevent further decay and/or restoration.

- **Renovation** (Rehabilitation) is the adoption and possible beautification of a structure in order to make it useful in modern needs.

- **Reconstruction** (*Anstylosis*) is the rebuilding of a faithful copy of a structure based on original period plans under a strictly supervision.

Another important issue, as an introductive point, in structural restoration is the recognition of historic structural system (material, structural system, et.c.) as compared with the historical period that was developed. For instance, in case of Greece, generally, one can distinguishes an ancient period using stone marble and wood as a connection element (in temples, colonnades) Byzantine and Post – Byzantine (Ottoman) period in which the masonry was used as a principle material in churches, towers, fortification constructions and neoclassical Greek period also with masonry, stone, and timber used as slabs and roofs. Also, local types of structural systems and local improvements of the basic structural material used make a project of restoration more difficult.

Having in mind all the aforementioned remarks an attempt is made in the followings to present and discuss some critical points concerning the structural restoration of historical monuments. Strategy, techniques and materials, as they applied in Greek practice, are given demonstrating the process of intervention.

### 2. PROCEDURES FOR AN EFFICIENT INTERVENTION

The preparation of an intervention work requires a series of decisions. These should be codified in a restoration project according to appropriate historical, technical and structural criteria. However, it is necessary that such a project must be prepared in a cognitive process of gathering knowledge and understanding of the building. This may include traditional and subsequent new materials, structural investigations, analysis and design as well as the identification of the historical, artistic and socio-cultural significance. Consequently, conservation techniques should be strictly tided to interdisciplinary scientific research on materials, technologies used for the strengthening or repair of historical monuments. It is indisputable that the chosen intervention should respect the original function and ensure compatibility with the existing materials, structures and architectural values.
In order to respect all the above statements, it is necessary to define a proper restoration methodology. Generally, there were no practical conservation standards or protocol of the best professional practice. However, a restoration process based on the E.C.A.E. (Engineering Center for Archeology and Environment) [4] comprehensive methodology and the experience of other countries is presented. The methodology consists of three phases, (Fig. 1):

- **Phase 1: Documentation**
  This includes historical studies, photography, surveying and architectural documentation in order to provide information on the following elements:
  - **Location** (Coordinates, accessibility, relation with surroundings)
  - **Historical records** (Date of construction, period, name of the constructor)
  - **Function** (temple, church, basilica, minaret)
  - **Architectural elements** (These elements are recorded with maps, drawings, sketches, photos, giving full description of these valuable elements)
  - **Type of material and structural system** (stone, brick, adobe, wood, marble, iron, their source and composition, articulated bearing system, stone – masonry system)
  - **Modification** (Alterations carried out by the different users, e.g. an orthodox church in a minaret)
  - **Restoration phases** (All previous restoration work executed over the life time of the monument)

- **Phase 2: Engineering Studies**
  This includes soil and foundation studies, building material studies, structural assessment, and fire fighting, in order to provide information on the following elements:
  - **Air quality** (Air is analyzed to determine the composition and concentration of pollutants)
  - **Subsurface water** (Analysis of subsurface water samples to identify the acidity, aggressivity of the water and salt content).
  - **Soil and rock properties** (Determination of geotechnical properties of different layers to evaluate the stability of foundations)
  - **Temperature variation** (Determination of the effect of diurnal changes on the local environment of the monument and the effects on moisture and grout content, dilation of cracks)
  - **Degradation phenomena** (diagnosis of diseases such as salting, sanding, cracking flaking)
  - **Structural stability assessment** (Recognition and investigation of major cracks that reduce the mechanical characteristics of the structural elements due to differential settlements in foundation or due to earthquakes)

- **Phase 3: Restoration Plan, Design and Intervention Measures**
  This phase includes the formulation of the appropriate restoration measures, after an extensive dimensional analysis, connected by technical specifications, engineering general and detailed drawings and bill of quantities. Planning of the works and managing of the side is strictly connected to this phase.
### 3. STRUCTURAL CONCEPT OF RESTORATIONS

The structural restoration (repair / strengthening) of old historical buildings is radically different from those of ordinary one due to a variety of parameters easy to understand from every one. Absolutely different structural materials and structural systems. Moreover, the mechanical behaviour of historic building materials and systems are no longer a subject of common technical education or current scientific research. The evolution, modification and changes of the initial load bearing capacity system through the time makes more difficult the restoration works. For instance, a truss member, which initially stabilize the walls acting as a diaphragm with the passing of time modifies its behaviour acting horizontal forces and developing tilting moments. For a structural engineer the intervention on historical monuments is a real temptation.

The main objective is to conserve the unaltered state of the architectural monument as close as possible from its original. It is therefore necessary to take into account the following principles, respecting the Venice Charter, [8,22]:

i) Restoration does not falsify the artistic or historic evidence

ii) When restoring monuments, use materials similar to that of the original

iii) Modern techniques and materials are admissible where adequate capacity cannot be ensured by traditional techniques. In this case durability and compatibility of the intervention should adequately proven [8,13].

---

**Fig. 1. Important phases in an integrated restoration methodology.**
iv) The principle of reversibility should be observed in restoration projects. The structural techniques should allow for removal or change without affecting the original.

v) Classifying the actions of an intervention, it is better to preserve than to restore, to restore than to reconstruct, to reconstruct than to do nothing at all.

vi) The less you change, the better or the minimum intervention is the maximum protection \[6,13,15\].

vii) Respect the contribution of all periods to the building. In case of necessary replacements the missing parts must integrate harmoniously with the whole but at the same time must be distinguished from the original.

First of all the recognition of the original materials as well as structural system should be made. Generally, historical monuments may be classified as articulated structures (e.g. ancient temples) and stone / masonry constructions (churches, towers, minarets). The main building materials are marble, stone, bricks, mortars, cast iron elements / clamps, timber, dowels, e.t.c.

Secondly, what causes the deterioration of monuments should be defined. However, both man and nature may cause the destruction.

- Man – made: wars, vandalism, neglect, ignorance, modernization, pollution, vibration, extreme loading (dead/live loading).
- Natural: extreme heat, humidity, insects, natural calamities (earthquakes, flood, fire).

From a strictly structural point of view damage may be produced by static actions (extreme dead / live loading, soil settlements, thermal variations, shrinkage of materials, e.t.c.) or / and dynamic actions (earthquake, machinery vibration, explosion).

- Static actions may be **direct** applied dead or live loads causing increased stresses in the elements, in case of changes of the use, space extensions, or **indirect** related to the deformation imposed on structures when these ones are not free to developed (differential settlement, temperature variation). Monumental structures are sensible to soil settlements, due to the lack of joints, massive structures. Especially, towers and minarets are very sensible to such phenomena due to reduced redundancy, stiffness and high ratio of height-span.

- Dynamic actions related to deformations imposed on structures caused primarily from earthquake accelerations. The behaviour of monuments in seismic areas is highly dependent on the earthquake parameters to which they have been exposed in their past history and the ground excitation to which are expected to be frequently exposed in future. Furthermore, earthquake actions are not considered in the initial design of historic buildings, consequently being more vulnerable than other structures. However, special studies regarding the seismic hazard, local soil conditions, dynamic characteristics and response of structural system must be planned.

An important step in structural restoration is the correct diagnosis of damage. Mainly, the crack pattern and deformations of the structure act as a guide for the evaluation of structural integrity. The observation of the effects of real earthquakes is fundamental in order to understand the seismic behavior of monuments. The studies of damaged monumental structures revealed that specific type of damage, as well as failure mechanisms, tend to reoccur in a quiet well identifiable part (Fig. 2) \[9,15\]. The great
variety of structural types, geometric typology and types of response makes the problem more difficult, needing special studies in order to classify all the above-mentioned issues. However, in diagnosis of damage in situ investigations and laboratory tests are very useful.

Based on the above results an analysis and design is proceeded for the assessment of structural response under conventional (gravitational) and exceptional (usually earthquake but also sometimes fire and impact loads) loading.

![Diagram of damage typology in Italian medieval churches](image)

**Fig. 2.** Observed damage typology in Italian medieval churches.
(Continued) Fig. 2. Observed damage typology in Greek churches.

After having identified the causes of damage and the kind of actions that have produced the damage, the restoration measures must be defined in order to safeguard the monument. The reanalysis of the new strengthened structure should be made in order to “theoretically” evaluate the effectiveness of the proposed intervention scheme. In figure 3, the basic steps concerning the engineering aspects, as it was defined in restoration methodology, (Fig.1), are presented.

Fig. 3 Engineering aspects necessary for the structural restoration of a historical monument
Considering the earthquake action as primary cause of damage a general scheme of intervention is discussed [1]. The aim is the reinstatement of the building's original antiseismic protection and possibly in accordance with the construction's value and a specific safety-economy point, an increase of the building's behavior against future seismic attacks. From all the above-mentioned remarks one can observe that the problem of structural restoration is concentrated on:

- Suitable methodology for structural documentation for the monument under restoration.
- Suitable choice of techniques and materials compatible with the original structure.
- Suitable choice of dimensional analysis and durable restoration measures facilitating a safe and cost-effective restoration project.

4. PRINCIPLES OF ANALYSIS, DESIGN DIRECTIONS AND RESTORATION STRATEGIES

There are basic difficulties in analysis and design of historical monuments due to the problems in determining the mechanical properties of the original materials (modulus of elasticity, compressive-tensile strength, Poisson ratio), which are necessary elements for the formation of constitutive mechanical models. Moreover, many uncertainties arise from the considerable strength variation or from a variety of brick and mortar types depending on the period of construction and the local area of the monument, (tab.3) [11,12].

| Table 3. Variation of mechanical properties (strength) of mortars and bricks. |
|---------------------------------|-----------------|-----------------|
| **Mortars**                     | **Strength (kg/cm²)** | **Binders**     |
| **Period**                      |                  |                 |
| Roman                           | 25-35            | Lime + Pozzolan +soil |
| 7th cent AD                     | 35-50            | Lime + Pozzolan +Brick dust |
| Ottoman                         | 10 - 15          | Lime > 40 %     |
| 18th cent AD                    | 10 - 15          | Soil +lime      |
| 19th. cent AD                   | Depend on cement content | Lime +cement |
| **Bricks**                      |                  |                 |
| **Period**                      | **Monument**     | **Strength (kg/cm²)** |
| 19 th. Cent. AD                 | Casa Bianca      | 100 - 210       |
| 19 th. Cent. AD                 | Mouson           | 80 - 100        |
| 19 th. Cent. AD                 | Mellisa          | 100             |
| 19 th. Cent. AD                 | Θ                 | 100 - 250       |

In order to reduce the above problems proceeding in a more reliable calculation, it is important to outline the following steps [1,13,17]:

- In situ investigations, including:
  i) Structural and geometrical survey using conventional surveying or photogrammetry methods.
  ii) Surveying of the damage.
  iii) In situ destructive test (e.g. core taking).
  iv) In situ non-destructive tests (e.g. ultrasonic tests, ambient vibration tests).
  v) Monitoring of cracks using proper measuring and acquisition systems.
  vi) In situ geotechnical investigations (excavation, bor-holes).
• Laboratory tests, including,
  i) Determination of the physical, chemical and mechanical properties of the original materials.
  ii) Determination of the mineralogical composition of mortars and grouts in order to obtain compatible materials.
  iii) Geotechnical tests on extracted soil sample.
  iv) Experimental investigation on prototype models (e.g. dynamic tests on shake tables simulating the condition of real earthquakes, measurements of dynamic properties of the prototype structure)

Having the preliminary elements necessary for the development of mechanical models the following steps should be made:
• Determination of the constitutive laws of the original materials (σ-ε curves, σ-τ curves, M-θ curves, e.t.c.)
• Determination of the dynamic response characteristics as fundamental period, damping.

Furthermore, the loading conditions should be stabilized:
• Determination of gravitational loadings considering all the dead and possible live loads (as a function of future use) acting on the structure.
• Determination of seismic safety level through design spectrum, considering the seismic risk of the area through microzonation studies.
• Combination of loads as provided by current codes. Special consideration should be made for the evaluation of real live loads in order to result realistic stresses conditions in elements.

Finally, before proceed to the analysis it is necessary to develop the computational model that simulates the structural system of the monument. The models must be simple enough to perform a large amount of parametric studies. It seems unrealistic to proceed sophisticated analysis when we have great mechanical and structural uncertainties. However, the computational effort required carrying out refined analysis (e.g. non-linear dynamic) is too heavy to be practicable from the common design offices.

With all the required elements established for the analysis, one can choose the suitable method considering the level of sophistication and reliability level:
  i) Static analysis with linear elastic laws using frame or shell elements.
  ii) Dynamic analysis with linear elastic laws using frame or shell elements.
  iii) Pushover analysis with inelastic laws in order to evaluate and simulate the formation of collapse mechanisms.
  iv) Time history analysis using selected accelerograms in order to evaluate the critical collapse loads as well as the collapse mechanisms in a ‘‘real’’ way.
  v) Finite element analysis considering different mechanical laws and types of analysis.

From the practical and scientific experience [2,5,9,13,15] should be outlined that static and dynamic analysis are necessary when the monument presents considerable cracks, deviations from the verticality, soil settlements. There is not a better index of structural efficiency for a monument than the fact of its survival for centuries without structural defects [13,14]. Moreover, the application of simplified mechanical models give a quantification of the maximum level of seismic actions that could sustained by the structure and also a quantification of the increase of strength due to some structural interventions.

For the design the considered laws (σ-ε curves, σ-τ curves), the principles of strength of materials as well as the considered failure criteria must be used.
In order to establish the restoration measures or the structural intervention strategy, it is absolute necessary to understand very well the original structural system, the capabilities of the original materials, the failure mechanism as developed from crack pattern, the behavior under static and dynamic loads. The experience of past events gives useful information in the design of the strengthening of historical monuments. Furthermore, the intervention strategies is strictly related with techniques and materials used in order to ensure durability and compatibility.

The basic strategies in structural restoration are [22]:

i) Local modifications of structural elements improving the connections of elements, strength and rigidity of elements.

ii) Global modifications of the original structural system reducing structural eccentricities or mass and rigidity discontinuities with new masonry walls or with new elements from reinforced concrete or steel elements.

iii) Reducing of mass, changing some heavy non – structural elements, controlling the areas in some spaces.

iv) Reducing of seismic forces with a scope of dissipating seismic energy, using elastomeric bearings at the base between foundation and upper structure or special hysteretic dampers in selected points in the building.

According to another classification taking into account the cause that produces the damage we could define strategies for damage produced by static loads, by dynamic loads and a combination of two.

For damage coming from excessive direct static loading (e.g. dead / live loads, snow):
• Simply strengthening of the original material by grouting, injecting resins.
• Local strengthening of vital structural elements.
• Global strengthening of the whole structure or modification of the original load bearing system.

For damage coming from excessive indirect static loading as soil settlements:
• Improving soil’s behaviour of the surrounding area.
• Modification of the pressures under foundations (enlargement of existing footings, drastic modification of the whole foundation system, micropilling).

For damage coming from excessive indirect static loading as temperature variation:
• Changing of structural system creating joints in specific points of the structure’s plan and cross section.
• Insertion of elastomeric pads in joints in order to dissipate the deformations.

For damage coming from dynamic loading:
• Improving structural behaviour with local or global modification of the structural system.
• Reducing the seismic effects with the insertion of suitable devices (elastomeric bearings, sliding systems, dampers).

5. MODERN TECHNIQUES AND MATERIALS USED IN RESTORATION

The main philosophy when we choose the suitable constructional techniques in structural restoration is to use materials similar to that of the original and/or to use traditional techniques. Durability and compatibility should be assured. A variety of problems arise due to the fact that sometimes it is difficult to recompose the traditional materials, it is also difficult to obtain the required strength with traditional compositions or
in many cases it is absolute necessary to introduce new incompatible materials in order to retrofit the old structure.

In this way, the modern techniques and materials should be used in a manner that will permit easy modification action, in the same time keeping the original historical value. Taking into account some basic parameters one can distinguish the following categories of structural techniques [3,5,13,17,19]:

i) Classification according to the mode of application:

**Reversible**, which are easy replaced without damage in the monument also respecting the original historical-cultural evidence. These techniques are, also, could be characterized as gentle.

**Irreversible**, which cannot be easily replaced in case of reintervention without damage to the original structure. These techniques are, also, could be characterized as drastic.

Gentle techniques, as a function of retrofitted structural element, are, (Fig. 4):

- **Foundation**
  - Underexcavation, for example modifying the pressures under the foundation increasing the soil deformability in the zones where the settlements are smaller than the others (materialized in the retrofitting of Pisa Tower, Italy).
  - Improvement of the soil’s behavior (e.g. soil nailing, grouting)

- **Masonry**
  - Confinement of masonry with linear steel bars.
  - Reinforcement of masonry wall with steel ties.
  - Rings at the base of domes (e.g. used in the restoration of Rotunda, [13]).
  - Ties at the springs of arches.
  - External prestressed or simple buttresses.
  - Using structural steelwork as a primary load carrying system keeping the exterior and interior masonry walls.

- **Timber**
  - Strengthening of an existing wood element (beam, roof) with steel plates.
  - Rehabilitation of an existing wood element with a new one.
  - Improvement of an existing wood diaphragm with steel or new timber elements increasing the strength and stiffness.

Drastic techniques, as a function of retrofitted structural element, are, (Fig. 5):

- **Foundation**
  - Modification of existing foundation system adding new R/C elements.
  - Enlargement of the actual foundations
  - Underpinning
  - Base isolation

- **Masonry**
  - Grouting and / or bonding new bricks.
  - Injection of epoxy resins in cracks and / or deep rejoining.
  - Rebuilding of a small, medium, or high part of a masonry wall.
  - Jacketing with gunite techniques.
  - Insertion of new R/C elements (beams, columns) at selected points (e.g. corners)
  - Confinement with fiber elements bonded on site with special epoxy adhesives in order to increase the tensile strength.
  - Replacement of an existing timber slab with R/C one.
- Movement of existing monument in other place using sloped ramps with railroad tracks, or with special cranes. The transportation technique is consisted by the uplifting of the monument and its transportation as a whole in a selected place (e.g. transportation of the O.S.E traditional building from Thessaloniki, transportation of the Torniki monastery from Grevena).

<table>
<thead>
<tr>
<th>MASONRY</th>
<th>Type of technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Rings at the base of domes.</td>
<td>b) Confinment of masonry with steel (titanium) bars</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>c) Steel truss elements</td>
<td>d) Reinforcement of masonry wall with steel ties.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIMBER STRUCTURES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>e) Improvement of an existing wood diaphragm with steel.</td>
<td>f) Strengthening of an existing wood element (beam, slab, roof) with steel plates.</td>
</tr>
</tbody>
</table>

Fig. 4. Reversible techniques used in structural restoration
- Timber
  - Replacement of a timber roof with R/C slab.
  - Injection of epoxy resins in cracks.
  - Strengthening of timber elements using fiber bars.
  - Jacketing with gunite techniques.
  - Insertion of new R/C elements (beams, columns) at selected points (e.g. corners).

ii) Classification according to the type of intervention:

- Repair is maintaining of a structure in order to extend its lifetime after a man-made or natural loading.
- Strengthening is maintaining and reinforcing of a structure in order to extend its lifetime after a man-made or natural loading.

**Repair techniques are:**

- Deep rejoining. It is recommended for stone structures of 30-40 cm wall thickness and masonry structures with cracks of 10mm depth.
- Injection of epoxy resins. It is recommended for masonry structures with crack depths larger than 10mm and thickness of walls larger than 40-50 cm.
- Steel reinforcing bars (ties). It is used when cracks are larger than 10mm, extensive diagonal cracks or disintegration of masonry walls.

**Strengthening techniques are:**

- Improving of soil behavior with different modalities (underexcavation, grouting).
- Improving of foundation system (enlargement of footings, radier, piles).
- Passive isolation systems reducing the seismic input energy (bearings, dampers).
- Jacketing the original structural system with R/C or fiber elements.
- Creation of diaphragms at the storey and/or roof level.
- Insertion of tendons, rings, steels bars.

Materials used very often in structural interventions of historical monuments are [1,13,19]:

- Cementious materials
  - Portland cement mortars and grouts
  - Lime cement mortars and grouts
  - Pozzolanic mortars and grouts
  - Epoxy resin mortars and grouts.

Generally, mortars for restoration must concord technically with old mortar and with the underlayer. Moreover, cannot be stronger or tighter than the original one and must have a low modulus of elasticity (cement mortars that are cement rich do not respect the above mentioned statement). The restoration mortar must be easy to remove, without causing damage to the original surface. It is easy to understand the contradictory demands imposed for the restoration mortars. Generally, lime mortars are characterized as “good traditional” and cement mortars as “objectionable”. However, it is not true due to the fact that both have variations depending of the type of binder, composition, grain size distribution of the aggregate, manufacturing and use. There is not possible to give strictly recipes, but general requirements should be set for materials used. Consequently, for the designing and fabrication of compatible restoration mortar is efficient if a holistic way of analysis will be followed [11]. Preferable is to use local materials (sand, soil, aggregates). Specific properties that should be ensured are strength, grain size distribution (gradation of aggregates), and porosity.
**MASONRY STRUCTURES**

<table>
<thead>
<tr>
<th>Type of retrofitting technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Insertion of new R/C elements (Beams, columns) at selected points</td>
</tr>
<tr>
<td>b) Base isolation</td>
</tr>
<tr>
<td>c) Grouting with epoxy resins or other adhesive material type.</td>
</tr>
<tr>
<td>d) Fiber bars increasing the tensile strength of a masonry</td>
</tr>
</tbody>
</table>

**FOUNDATIONS**

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>e) Strengthening with micropilling</td>
</tr>
<tr>
<td>f) Retrofit adding R/C beams</td>
</tr>
</tbody>
</table>

**Fig. 5.** Irreversible techniques used in structural restoration.
• Synthetic (composite) materials, (Tab. 4a,b):
  - Glass fibers.
  - Carbon fibers.
  - Kevlar 29 fibers
  - Aramid fibers.

**Tab. 4a.** Characteristic properties for synthetic materials

<table>
<thead>
<tr>
<th>Type</th>
<th>E (GPa)</th>
<th>σ_tensile (Mpa)</th>
<th>ε (%)</th>
<th>Aprox. Cost (euros)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fibers</td>
<td>81.0</td>
<td>3400</td>
<td>4.90</td>
<td>45.0</td>
</tr>
<tr>
<td>Carbon fibers</td>
<td>160.0 – 270.0</td>
<td>1400 - 6800</td>
<td>1.0 – 2.50</td>
<td>55.0</td>
</tr>
<tr>
<td>Kevlar 29 fiber</td>
<td>62.0 – 83.0</td>
<td>2800</td>
<td>3.60 – 4.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Aramid fibers</td>
<td>120.0</td>
<td>3000</td>
<td>3.0</td>
<td>45.0</td>
</tr>
</tbody>
</table>

**Tab. 4b.** Mechanical properties for composite materials (fiber and resin)

<table>
<thead>
<tr>
<th>Composite material</th>
<th>E (GPa)</th>
<th>σ_tensile (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass - resin</td>
<td>35.0</td>
<td>400 – 1500</td>
</tr>
<tr>
<td>Carbon – resin</td>
<td>140.0</td>
<td>800 - 3000</td>
</tr>
<tr>
<td>Aramid - resin</td>
<td>60.0</td>
<td>1400</td>
</tr>
</tbody>
</table>

• Metallic materials
  - Stainless steel, which can be normal steel protected with zinc, epoxy-resin or other chemical material against corrosion or steel with special composition (Ch-Ni-No).
  - Titanium bar members, which have exceptional anticorrosive properties.

• Other elements treated as materials, (Fig. 6)
  - Rubber bearings or friction pendulum bearings, modifying the dynamic response of the system.
  - Hydraulic / hysteretic dampers, dissipating seismic input energy.
  - Shape memory alloy devices, S.M.A.D., which have the ability to undergo large strains, while recovering their initial configuration at the end of the deformation process. Thus, absorbing seismic input energy without permanent deformation.

<table>
<thead>
<tr>
<th>Rubber bearings</th>
<th>Hysteretic damper</th>
<th>S.M.A.D. devices</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Rubber bearings" /></td>
<td><img src="image" alt="Hysteretic damper" /></td>
<td><img src="image" alt="S.M.A.D. devices" /></td>
</tr>
</tbody>
</table>

**Fig. 6.** Irreversible techniques used in structural restoration.
6. CASE STUDIES OF GREEK HISTORICAL MONUMENTS

6.1 Restoration of ancient monuments

Generally, ancient monuments due to long period of lifetime and high degree of disintegration need an intervention named anastylosis. The main constructional material used is marble or cut stone and the fundamental load bearing system is an articulated system with ‘‘dry’’ joints, (Fig. 7). Such systems are sensible on sliding, rotation and rocking, being very complex phenomena, which are not well studied till now. Recently, a great effort is made in order to understand the above-mentioned influences [10,19].

A characteristic example of restoration of such monuments is the Anastylosis of Acropolis complex from Athens (constructed between 447 –430 BC), [20,21].

Typical damage, which can be observed, is cracking, breaking and splintering of the marble caused by displacements of earthquakes, fires, explosions or earlier interventions. Also, the insertion of reinforcing bars in dry joints that had been introduced in earlier interventions caused extensive rusting. Another important damage factor is the atmospheric pollution deteriorating the marble surfaces, also reducing the cross section and creating possible phenomena of instability in case of severe seismic actions.

The intervention techniques exploit the articulated system dismantling all the structural components in order to undergo conservation on the ground or in some special cases in laboratories. The old rusted metal connectors are removed and then rejoined using titanium bars, dowels and cement compound in order to rehabilitate the whole integrity of the system. Recently, special devices (shape memory allows, which are wires of 1-3mm cross section) are developed dissipating the input seismic energy ensuring a better dynamic behavior of columns and colonnades [10]. It is necessary, especially for reasons of structural stability some parts filled in with new Pentelic marble in such a way as to be reversible, using the same method as that applied to the copies of sculpture [21]. The surface of monuments are treated with spaying impregnation filling and injections with organic materials, that are reversible demonstrating a satisfactory behavior over a period of time.

<table>
<thead>
<tr>
<th>Basic structural system of ancient monuments</th>
<th>Columns dismantled undergo conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Basic structural system of ancient monuments" /></td>
<td><img src="image2.png" alt="Columns dismantled undergo conservation" /></td>
</tr>
</tbody>
</table>

Fig. 7. Greek ancient structural systems and its restoration.
6.2 Restoration of Roman and Byzantine monuments

From structural point of view, recognizing the traditional structural system of Roman and Byzantine monuments one can observe masonry structures with vaults, arches or domes strengthened with timber elements, (Fig. 2).

A variety of Roman and Byzantine monuments (Rotunda, Acheropiitos church, St. Pantelimon church) exists in Thessaloniki, which have seriously damaged after a severe earthquake in 1978. A great research effort was made from the University of Aristotle, Thessaloniki, in order to safeguard these values [7,13,14,18].

Trying to organize the experience captured of restoring such buildings, the main steps are presented in short, as follows:

The first step was the suitable propping due to stability problems, using external timber propping, erecting steel propping systems in order to ensure the possibilities of extensive investigations of damage, as well as, the repair and strengthening works, application of provision prestressed tendons or rings avoiding further displacements, (Fig. 8).

![Fig. 8 Propping of monumental structures](image)

The second step was the detailed surveying of damage, monitoring of deformations using extensometers or glass ‘‘witness’’ measuring vertical / horizontal displacements and the evolution of cracks, in situ and laboratory investigation concerning the evaluation of the mechanical and chemical properties of the original mortars and bricks in order to recompose such materials for the intervention stage.

The third step was the evaluation of damage. It was observed that the higher part of the monuments suffer more pronounced cracks as compared to the lower one, due to the fact that vaults creates pressures and as a consequence developing deformations in masonry walls. The phenomenon was produced due to strength reduction of the original system as the time was passed, also in case of seismic action aggravating the situation, (Fig.2) Geometry of monument is an important damage factor. For instance, towers and minarets are slender structures sensible to soil settlements and vertical seismic excitations.

The forth step was the analysis and design of intervention schemes. A very difficult task is the modeling of the structure. Generally, arches, masonry walls, timber members are modeled as beam elements and the soil with spring elements, (Fig.9). A step-by-step limit state analysis was performed in order to reproduce the observed crack patterns and possible failure mechanisms. Alternative schemes of the original and the retrofitted solution were analyzed.
The fifth step was the repair and strengthening of the original structure using reversible (steel ties, rings, confinement with titanium bars) and irreversible (grouting, deep rejoining, thin jacketing from R/C) techniques, (Fig. 3,4).

<table>
<thead>
<tr>
<th>a) Real structure</th>
<th>b) Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Real Structure" /></td>
<td><img src="image2" alt="Simulation" /></td>
</tr>
</tbody>
</table>

**Fig. 9.** Simulation for analysis requirements [7].

### 7. CONCLUDING REMARKS

The basic goal of structural restoration of historical monuments is to conserve them with best possible techniques and materials, as well as with the use of the best manpower available to carry out the work. The Venice Charter acts as a conceptual guideline for any structural intervention. Moreover, the interdisciplinary approach used in all phases of the restoration projects should be considered.

It is worth to notice that it is better to keep the original structural system than to modify. From the experimental and analytical work was demonstrated that the minimum intervention is the maximum protection.

As a concluding remark should be outlined the lack of practical recommendations for structural interventions on historical monuments, a necessary document that will help all the professionals implicated in restoration works.

### 8. BIBLIOGRAPHY


