Draft FRAMEWORK REGULATORY DOCUMENT for structural interventions to and seismic protection of MONUMENTS

INTRODUCTION

1. The significance of the seismic resistance of monuments

The seismic resistance of monuments (available or required) is important for two reasons:

(a) The present generation feels the need to ensure (as much as possible) the survival of this Cultural Good, against the seismic risk which may cause damages or even collapse ("Integrity of the Monument"). To this end, we are requested to study various measures of structural intervention (i.e. repair and/or strengthening) which should alter the least possible the monumentic values.

It is nowadays admitted that our decisions on the matter are not fully covered by the view that "a monument that has sustained past earthquakes, will also sustain the future ones".

i. In most cases, previous earthquakes have already caused light or heavier damages to the monument; their accumulation may reduce in a non predictable way its available seismic resistance against similar earthquakes in the future. This is more so, because other deleterious actions (such as physicochemical decay, creep effects, fire, foundation soil modifications, as well as various human actions) have caused further reduction of the bearing capacity of the monument.

ii. According to both the theoretical and the statistical seismology, the occurrence of more severe earthquakes (in terms of accelerations/velocities/displacements and-more frequently-in terms of spectral content) in the future cannot be excluded.

(b) In addition to the "preservation" of the cultural heritage itself, the interest for the seismic resistance of a monument is dictated by the legal endeavour of the protection of the lives of neighbours, conservators, visitors or inhabitants of the monument. This second aspect of our interest for the seismic behavior of monuments (depending on their "visitability") becomes more and more significant in modern societies that attribute a high value to the human life.

2. Current difficulties related to the subject

During the design of interventions to ancient, byzantine-post byzantine and contemporary monuments the Engineer faces difficulties, namely:

The high uncertainty related to the estimation of the resistances of materials and bearing elements, of the actions, as well as of the methods for analysis and verification. Within the Ministry of Culture and Tourism and the Technical Chamber of Greece, efforts were made in the past for drafting Specifications, the design of structural interventions should comply with. Such specifications are applied mainly in the case design of interventions is carried out within the Ministry. Nevertheless, (a) the legal status of those specifications does not allow for their general application and (b) the number of designs of interventions carried out within the Ministry regards only a small percentage of monuments. It should also be noted that the existing Specifications leave the decision about crucial parameters within the hands of the Engineer; thus, a viable and rational solution to the problem of responsibility in case of further damages is not provided.

The lack of a specific regulatory document for the rationalization of the design process, in case of monuments, leads the Structural Engineers to treat the monuments using the methodology and the Design Codes applicable to new structures. Thus, quite often drastic (and invasive) interventions are proposed. Those interventions alter the original form of the monument, whereas they are not reversible. The plausible argument of Structural Engineers is that they have to apply the current Codes, although in the latter it is clearly stated that they are applicable exclusively to new structures. The truth is that the Structural Engineer cannot take the (legal and moral) responsibility of reducing the severity of design criteria in case of monuments.

The current situation leads to “frictions” between Structural Engineers on one side, Archaeologists and Architects on the other side. Thus, in several cases, the Ministry of Culture and Tourism (based on the consultancy of relevant Scientific Bodies) approves only that part of the proposed (by the Structural Engineers) measures that do not affect the values of the monument. The question is posed, however, about “who is responsible for the losses in case of an earthquake?”, in terms of damages in the monument itself, in its valuable content and, of course, in the life of visitors or occupants.

There is therefore an obvious and urgent need for a regulatory document on the design of structural interventions to monuments.

3. The initiative of the Ministry of Culture and Tourism and the Earthquake Planning and Protection Organization

In 2004, within the Earthquake Planning and Protection Organization (EPPO), a Committee was appointed with the mission to draft a Framework for a Regulatory Document on the structural interventions to monuments. The Committee has prepared the current text and it has also made suggestions regarding the actions to be taken with the purpose of preparing such a Regulatory Document.

The drafting of such a Regulatory Document requires the appointment of a large multidisciplinary Committee, of Working Groups, as well as the funding of supporting research work, etc.

4. The purpose of the current "Draft Framework Regulatory Document"

Due to the high importance of the subject, within EPPO the decision was taken to prepare in a more organized way the work of a large drafting Committee. For this purpose, a 15-member Committee was appointed with the mission to prepare the current draft Framework for a Regulatory Document.

PART A: FUNDAMENTAL NOTIONS

1. The Contradicting values

The seismic behaviour of Monuments is very important in earthquake prone areas because of the cultural need to maintain and inherit these Monuments to future generations. Furthermore, the need to ensure seismic resistance to the Monuments is ensued from the legal obligation to protect human life (of the neighbours, curators, visitors or even inhabitants of the monument).

To this end, more or less drastic structural interventions are often implemented, aiming to an adequate level of repair or strengthening of the monument with the lowest possible consequences on its "monumentic" values.

The preparation of design documents regarding the aforementioned adequate structural interventions is frequently facing several *difficulties*, not encountered in the case of common (non-monumental) buildings, such as:

- Additional uncertainties related to the available resistances of building components
- Particularities in selecting the appropriate method of Analysis, suitable (i) to a given typology of the Monument and (ii) to the level of resistance uncertainties
- Difficulties in selecting
  - An appropriate design value of seismic action, such that the respective necessary intervention will not jeopardize the monumentic values of the Monument, and
  - Appropriate Techniques with an optimum level of reversibility/re-interventionality.

Because of these difficulties, the preparation and/or approval of design-documents is frequently the cause of controversial discussions between Engineers, on the one hand, and Architects and Archeologists, on the other.
These controversies are but a reflection of the contrarieties between the following "Principles" (Values and Requirements) related to the structural interventions in Monuments:

(a) *Monumentic*[1] *Values*

a1: Form (aesthetic value).

a2: History (symbolic value).

a3: Preservation of ancient building-Techniques and Materials (technical value).

(b) *Social Values*

b1: Preservation of the cultural Memory of a Monument (integrity, survival).

b2: Adequate safety against normal actions and Earthquakes (value of human life).

b3: Modern use of Monuments.

b4. Cost-reduction of the structural intervention.

(c) *Performance-Requirements regarding the structural intervention* (Intervention Values)

c1: Reversibility level and or re-interventionality level

c2: Durability

c3: Technical reliability

Every intervention aiming at a structural repair or strengthening of a Monument entails some inevitable *harm* to several of these values and performance-requirements, depending on the actual condition of the Monument and the available technologies. Nevertheless, the final decision for the selection of the adequate interventions should be taken on the basis of an optimization of "Principles", which could lead to a partial violation of the "set of Principles".

In this respect, it is reminded that such an optimization cannot be reached by means of just "scientific" judgments: The values entering the game are of different nature; they are *not* amenable to identical "units"—they are not quantitatively comparable between each other! That is why, in the field of structural interventions of Monuments, only managerial (almost political) decisions are feasible; weighing factors for each of these Principles may be (directly or indirectly) discussed within an interdisciplinary group, and a final "optimal" decision be made.

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[1] This neologism is a very useful term to express concepts related to Monuments, avoiding however the possible confusion with the secondary meanings of the term "monumental" (i.e. impressively large, outstanding, astounding).

Such an optimization process, directly affects some important technical issues related to the seismic (re)design of Monuments: The design value of seismic actions has to be decided taking (also) into account its eventual consequences on monumentic values, too, as well as on costs and technical performances. Thus, a sort of "negotiation"[2] of design seismic actions is initiated: Disproportionately high design-values, serve the "human life" and the "integrity" principles, but they may jeopardize some monumentic values and performance requirements.

Therefore, a better overall intervention (an "optimal" solution) may be sought, based on possibly lower design-values of seismic actions, i.e. on higher exeedance probability. The same holds true for the selected intervention schemes and technologies; they should also be finally decided following a similar optimization process.

In order to facilitate such a decision making process, further rationalization of data is needed regarding the "Importance" of a given Monument, as well as its "Visitability" level.

2. Importance, visitability and acceptable damage-levels

- The design-value of the seismic actions to be taken into account for the re-design of Monument's structure may also depend on acceptable damage-levels, which in their turn will be decided on the basis of the importance of each Monument. That is why in many Countries, a *categorization* of Monuments is available to designers, as follow:

  I_1: Monuments of universal importance
  I_2: Monuments of national importance
  I_3: Monuments of local interest

- Another useful tool towards a rationalization of decision making regarding structural interventions, is the categorization of the occupancy of Monuments: Higher occupancy means higher concern for human lives against earthquakes, and therefore higher seismic actions' design values. That is why engineering decisions would be facilitated if a

[2] It should be noted that design seismic actions regarding modern buildings are *also* negotiable: The socially acceptable "probability of exceedance" of seismic actions imposed by actual Codes, depends on several variables, such as the actual economical level of the Country and the social importance of the building, i.e. on non-scientific data. The difference with Monuments is that in this case, such a "negotiation' is taking place within a broader *multiparametric* space, including many additional Values and Requirements.

"**visitability**" categorization of Monuments would be made available, such as in the following list:

V_1: Almost continuous presence of public or frequent presence of large groups
- – Inhabited buildings in historical city centres
- – Monuments used as Museums
- – Monuments continuously used for worshipping

V_2: Occasional habitation or intermittent presence of small groups
- – Monuments visited only under specific conditions
- – Remote and rarely visited Monuments

V_3: Entrance allowed only to Service-Personnel. Visitors stand only outside the Monument.

• Combining the aforementioned "Importance-levels" and "Visitability-levels", it is possible to decide "*Acceptable Damage-levels*" ("I" for negligible damage, up to IV for serious damage), under the re-design earthquake.

Such a possible matrice is given here below (indicatively though):

ACCEPTABLE DAMAGE-LEVELS (I–IV) UNDER THE RE-DESIGN SEISMIC ACTIONS		PREVAILING VALUES			
		Human life and monument's integrity **(*)**			Form and history (aesthetic and symbolic value)
Visitability		**V_1**	**V_2**	**V_3**	
Importance level of the Monument	**I_1**	**I**	**II**	**II**	**I**
	I_2	**I**	**II**	**III**	**II**
	I_3	**II**	**III**	**IV**	**III**

(*) The integrity of the monument is considered here together with the human life for practical reasons, as in fact whatever is in favor of the human life, is also in favor of the monuments integrity (however, this does not mean that higher level of visitability alone could lead to lower damage level).

To this end, a systematic description of each damage-level is needed, separately for traditional masonry buildings, arched structures or domes, and greco-roman monuments. It is believed that such an approach may substantially facilitate rational decision making, related to structural interventions of Monuments against seismic actions.

PART B: THE CONTENTS OF THE DESIGN OF INTERVENTIONS

1. DOCUMENTATION OF THE MONUMENT AND RELIABILITY LEVEL OF DATA

The Structural Design constitutes an integral part of the entire study of the monument. Therefore, the files of the Structural Design, submitted for approval, should obligatorily include also those data regarding the history and the architecture of the monument, which are necessary for the Structural Design.

1.1 Contents of the Structural Documentation

(a) Brief history of the monument and references to the ancient and/or contemporary literature, with emphasis on matters that may be of significance for the structural aspects of the monument.

(b) Architectural documentation (Report, drawings and photographs), with emphasis on the geometry/morphology, as well as on the construction phases of and interventions to the monument.

(c) Report on the survey of damages, repaired or not ("pathology"), as well as of their in-time development after the commencement of the study.

The surveyed damages are reported on the drawings of the architectural survey. In addition to the damages that may be mentioned in the History of the Monument, the identification and the description of damages is done using various methods, mentioned herein in an indicative way though:

–Careful and systematic visual observation of all details of each bearing element.

–In situ measurements, using simple means

–Measuring and experimental methods for the investigation of materials and the identification of damages hidden under ulterior plasters or other interventions.

The in-time development of those damages, after the commencement of the investigation of the monument are usually of great interest and it has to be monitored:

- Through measurements taken at intervals
- Through an installed monitoring system, as described in an indicative way in para 1.1g

(d) Description of previous structural interventions, with the purpose of (i) identifying the vulnerable parts of the structural system, (ii) identifying the time of occurrence of previous high value actions and (iii) judging on the efficiency of those previous interventions.

(e) Systematic survey and description of the in situ state of (i) materials, in terms of their nature, the extent of their use, the possible time of their insertion to the monument, their actual properties (including their in-time development) and (ii) the connection of the two exterior leaves of masonry (e.g. through header stones), within the thickness of the elements.

For this purpose, relevant experimental methods are applied, in situ or in laboratory (see para g)

(f) The survey of those investigations is reported on the drawing of the architectural documentation.

The extent and the depth of the investigation of materials does depend on

(i) the importance of the monument and

(ii) the probable causes of the structural vulnerability of the monument

(g) Results of application of experimental methods, which may serve the following needs of the Design:

(i) General arrangement of the bearing system: Laser scanning, photogrammetry

(ii) Identification of the structural system (of the bearing system):

–Connection between meeting walls: e.g. Radar, boroscopy

–Hidden openings and discontinuities in-plane: Thermography

–Discontinuities and voids within the thickness: e.g. Radar, boroscopy

–Eigen period, eigen modes: Dynamic tests

–Identification of metallic objects: Magnetic methods, radar

(iii) In situ strength of materials

–Stones: Rebound test, scratch method, ultrasound measurements

–Filling material of three leaf masonry: core taking

–Mortars: Scratch method, penetration test

–Timber: Penetration test

–Metals: Sclerometre measurements

(iv) Resistance of critical regions

–Compressive and shear: In situ, using flat jacks (or laboratory tests on wallettes taken from the monument or on wallettes simulating the in situ masonry

(v) Durability:

–In situ measurements of water penetrability, alkalinity, etc.

–In laboratory measurements of porosity, chemical alterations, etc.

On the other hand, the in time development of all the properties of the monument will be monitored and recorded, mainly for the following characteristics:

–Displacements: Wire extensiometres, pendulums, clisiometers, laser

–Settlements: e.g. clinometers

–Internal forces: Incorporated dynamometers

–Humidity: Thermography, radar

–Cracks: Deformationmeters (LVDTs, strain gauges)

–Seismic actions: Seismometers, accelerometers

–Environmental actions: e.g. Thermometers, solar emission meters

–Water table level: pressuremeters

(h) Description of the structural system, i.e.:

–Identification of the function of the bearing elements

–Description of the connections between bearing elements

–Description of the construction type of each element

Experimental methods may be needed in some cases for this purpose.

(i) Description of the foundation and the foundation soil, using

–Descriptions included in the History of the monument

–Indications from neighbor structures or excavations

–Soil boroscopy, whenever possible

–Results of soil drilling, wherever allowed

(j) Information on the behaviour of other monuments with similar structural system or (where the materials matter) with similar materials and environment. Relevant Authorities provide the Engineer with existing databases.

1.2 Evaluation of the Documentation of the Structural System

Those involved in appointing the Designer, in the design, in supervising and in approving the structural design to a monument should take the maximum profit of the structural documentation, so that to reduce as much as possible the uncertainties related to

-The geometry of the structural elements,

-the multiple hidden discontinuities,

-the strength of the constituent materials

-the resistance to compression, shear and flexure of critical regions of the structural members.

Those uncertainties, that may be accumulative, may make useless the results of any analytical work to be subsequently carried out with the purpose of calculating the action effects on the structural members.

1.3 Levels of reliability of data

Such a distinction between levels of reliability serves the purpose of assessing the uncertainties (and, indeed of the inevitable lacunae) of the available documentation data.

On the other hand, such a distinction is necessary, so that to reach harmonization between:

-the reliability of the data, on the one hand, and

-the method of evaluation of those data (regarding, for example, the sophistication of the method of analysis, as well as the models for the assessment of resistances).

Otherwise, the result of calculations will be characterized by “non harmonized” accuracy, i.e. it will risk to be unreliable.

2. METHODS OF STRUCTURAL ANALYSIS

A. Monuments with masonry structural system

2.1 Available methods of structural analysis

a) For the purpose of calculation of the action effects needed for the assessment of the monument, as well as for safety checks, before and after interventions, in principle, all available methods of structural analysis can be used, namely:

- Linear elastic analysis with global behaviour factor q (see 2.4.1)
- Linear dynamic analysis with global behaviour factor q (see 2.4.2)
- Non linear static analysis (see 2.5.1)
- Non linear dynamic analysis (time-history analysis) (see 2.5.2)

b) Because of the more or less complex structure of monuments and the limited knowledge of their seismic response, the use of the non linear dynamic analysis is not recommended herein. Such analyses may be performed only by specialized Civil Engineers, provided that this is agreed upon by competent Authorities.

c) The entire monument or critical parts of it may be analysed.

2.2 General criteria for the selection of the method of analysis

a) For the selection of a suitable analysis method the following aspects are taken into consideration:

- The ability of the method to describe the exhibited behaviour of the monument
- The structural form and the dynamic characteristics of the monument
- The accepted level of damage during the earthquake considered for the redesign

b) Criteria related to the structural form are:

- The size and the complexity of the monument
- The structural regularity of the monument
- The dynamic characteristics of the monument

c) Due of the complexity of the structural system of monuments and the uncertainties related to the constituent materials, an important criterion for the selection of the method of analysis is the ability of the method to interpret the exhibited behaviour and, especially, the cause of existing damages.

d) The combination of methods and models (e.g. elastic analysis for the entire structure and inelastic analysis of selected subassemblies) may constitute the most adequate choice.

2.3 General criteria for a reliable modelling

a) The computational model of the monument consists in the load bearing system and the non structural elements that are necessary for the study of the selected performance level, independently on whether the entire structure or critical parts of it are considered for the analysis.

b) Depending on the case, the discretization of the structure may be performed using one of the following methods:

- The finite element method using, preferably, shell elements.
- Sensitivity analyses are, in principle, required, due to the fact that the results of analysis depend usually on the mesh size.
- The equivalent frame approach in which the piers correspond to columns and the spandrels to beams. The joints must be modelled as rigid members.
- Macro-elements, i.e. modelling each part (pier, spandrel or a part between cracks) of the structure by a macro-element. This approach is appropriate when either linear or non linear analyses are carried out; however, only specialized Engineers are entitled to apply this method.
- Modelling part of the structure as a kinematic mechanism, analyzed using a kinematic (linear or non-linear) method. This method is preferred especially when the out of plane behaviour of parts of the structure is examined.
- Modelling the critical part of the monument as a combination of struts and ties. The weak point of this method is the determination of the geometry and the properties of the system of struts and ties.

2.4 Elastic analysis

2.4.1 Elastic static analysis

To judge about the applicability of the method, a preliminary linear elastic analysis is performed and the ratio of the elastic demand to the resistance of each primary member is calculated

$$\lambda=S/R_m$$

2.4.1.1 Criteria for the applicability of the method

a) For all primary members λ≤2 or for one or more primary elements λ>2 but the structure may be assumed to be regular.

b) The fundamental period of the structure is $T_0<3.5T_2$

c) The ratio of the horizontal dimension of one floor to that of the adjacent floor is not greater than 1.5 with the exception of the upper floor

d) The structure is more or less symmetric in plan

e) The structure is more or less symmetric in elevation

f) A system of shear walls arranged along two almost orthogonal dimensions is available.

g) Independently of the fulfilment of the above requirements, and under the restriction that the structure is undamaged, elastic static analysis is permitted only for the assessment of the monument using adequately increased partial safety factors.

2.4.1.2 Modelling

a) The criteria of section 2.3 are fulfilled.

b) The properties of the members are based on the elastic stiffness and viscous dumping.

2.4.1.3 Distribution of seismic action

a) The base shear along each axis is calculated by the current Seismic Code.

b) The distribution of shear over the height is made according to the fundamental eigenmode.

c) In the case of rigid floors, an additional accidental eccentricity is taken into consideration

2.4.1.4 Proper form of resulting action effects for verification

a) Forces and deformations are calculated using the equivalent static analysis (see 2.4.1.3)

b) When stresses are calculated (using a finite element method), integration of stresses should they should be performed over the length of each section in which a safety check is carried out.

2.4.2 Elastic dynamic analysis

2.4.2.1 Criteria for the applicability of the method

The method may be applied when, for all primary members $\lambda \leq 2.5$ or for one or more members $\lambda > 2.5$, but the structure is regular.

2.4.2.2 Modelling

a) The criteria of section 2.3 are fulfilled.
b) The properties of the members are based on the elastic stiffness and viscous dumping

2.4.2.3 Seismic action

a) The dynamic analysis will performed using adequately large number of eigenmodes (from modal response spectrum analysis)
b) The combination of maximum values of action effects (in terms of forces or deformations) is performed according to the current Aseismic Code.
c) Mode superposition will be done according to the current Aseismic Code.

2.4.2.4 Proper form of results for safety evaluation

c) When stresses are calculated (using a finite element method), integration of stresses should they should be performed over the length of each section in which a safety check is carried out.

2.5 Non linear analysis

2.5.1 Non linear static analysis

2.5.1.1 Basic assumptions of the method

a) The non linear properties of members will be taken into account. In case the "equivalent frame" is used for the modelling, the non linear relation of M-θ at both ends of each pier and spandrel, taking into consideration additional rotations due to shear, will be implemented in the model.

b) The model will be subjected to horizontal actions (distributed in proportion to the inertial [seismic] forces). The seismic forces will increase monotonically until an element becomes unable to take its vertical loads. From this analysis, the resistance curve of the structural system is calculated. That curve is used for the safety checks at the selected performance level.

c) After the selection of the seismic action (for assessment or for redesign), it is checked whether the control node of the structure fulfils the criteria of the selected performance level (in terms of displacements). It is verified that for the calculated displacement, the ductile members of the structure are not damaged beyond the level acceptable for the adopted performance level.

2.5.1.2 Criteria for the applicability of the method

a) Non linear static analysis is carried out to structures in which the higher eigenmodes do not contribute significantly to the response (see 2.4.1.1.b).

b) When the contribution of the higher eigenmodes is significant, the method may be applied under the condition that it will be combined with a linear dynamic analysis.

2.5.1.3 Modelling and analysis

a) The vertical and the horizontal loads will be combined, according to the combination rules set in the current Seismic Code. The verification of structural members is carried out for the most unfavourable combination of action effects.

b) Meshing will be adequately selected, in order for the force-deformation curve of the candidate inelastically performing region to be taken into account.

c) In case of plane analyses, two models representing the bearing system along the two orthogonal directions may be used. Otherwise, a space model of the entire structure should be analysed.

d) The control node for the calculation of the target displacement is generally taken at the centre of mass of the uppermost level of the structure. In case there are setbacks, the control node is taken at the top of the storey below it.

2.5.1.4 Determination of seismic actions

a) Seismic loads are distributed according to the fundamental eigenmode along the examined direction. At least two different distributions are required along each direction.
b) In case of flexible floors, their flexibility has to be taken into account in the model. The target displacement may be calculated by means of methods which consider both the non linear response and the torsional effects, based on modal response spectrum analysis of a space model of the structure. Alternatively, the target displacement may be calculated for each individual load bearing system representing part of the monument.
c) In case of rigid floors, the target displacement may be calculated by methods which take into account both the non linear response and the torsional effects, based on modal response spectrum analysis of a space model of the monument.

3. ESTIMATION OF THE RESISTANCE OF CRITICAL REGIONS

1.1. Evaluation of resistances under mechanical actions

One of the most significant particularities of the structural re-design of Monuments is the difficulty to determine the resistances of critical regions of stone masonry structural elements, with accuracy compatible to the accuracy of the calculation of the action-effects. Thus, the inequality of safety ($E \ngtr R$) becomes a rather loose condition, leading to either overconservative or to unsafe solutions.

This unpleasant situation is partly due to the fact that the available scientific methods for evaluating resistances of historic masonry structures are either insufficient or difficult to be applied. This fact is not always easily understood, as the subjects related to Analysis (S) are much more developed and their glamour may hide the lack of reliable Resistance (R) evaluation.

In the field of structural assessment and re-design of Monuments, it is of a paramount importance to overcome this scientific weakness, as this could lead to a need of violation of other important monumentic values; thus, every effort is justified in order to better evaluate the available resistances of critical regions of “masonry” walls, or “cut stones/dry joints” structural elements.

To this end, empirical formulae or simple rules of thumb alone do not serve the purpose: Detailed preliminary inspection and in situ experimental investigation will be the indispensable basis for any subsequent computational step of resistance determination.

This need is more pronounced in the case of important monuments (in comparison with a common historic building) and in all cases it is absolutely justified by the fact that an old structure had not the possibility to be built under fully controlled conditions of design and construction, as it is imposed in the case of a new building.
That is why in this regulatory document the proposed methods are more specialized and detailed than those used in common new structures.

3.1.1 In-plane resistances of masonry with mortar

3.1.1.1. Strength and deformability in compression perpendicular to masonry layers

(A) Semi-analytical strength evaluation

a) The following data are firstly needed in order to evaluate the basic resistance characteristic of a masonry, i.e. its compression strength perpendicularly to its layer:

- Detailed survey including the under scale indication of blocks and joints
- Photographic view of the face of each critical region of the wall or pillar, on which a sufficient number of vertical sections is traced (5 to 10), representative of the level of blocks interlocking
- Calculation:
  - Of the sum of the mean values of intersected blocks Σh_b divided by the total height of the examined area ($\Sigma h_b : H$)
  - Of the mean value of thickness of quasi horizontal joints, divided by the mean value of the height of blocks ($\Sigma t_j : h_{bm}$).

b) Subsequently, the construction type of masonry within its thickness is examined. Therefore, direct observation through temporarily opened holes or televisioned endoscopy or even georadar (and or sonic tomography) may be used. In Monuments of lower importance, some transverse core-takings may also be helpful.

   The aim of this endeavour is to obtain the most reliable image of the interior of the masonry, in order to find out if the wall may be considered as one-leaf or two (or three)-leaf masonry. Furthermore some information for the type of voids and their percentage is also sought.

c) On the basis of the above information it will be decided to which structural category the masonry under examination would belong. Moreover, the liability level of this information should be estimated.

   [The final regulatory document will include illustrated examples of the above necessary data, as well as criteria for the classification of the masonry in structural categories, taking into account the combination of the aforementioned characteristics, especially those concerning the interlocking of blocks both in the façade and perpendicular to it. It will also contain recommendations for the use of arithmetic coefficients in order to take into consideration the above structural categories to the calculation of strength.]

d) Determination of compressive and tensile strength of blocks and mortars

   i) By sampling and laboratory tests

      The samples of blocks have to be representative of the petrografic composition and of appropriate volume. As regards mortars, the sampling is more delicate. Usually small pieces are tested in direct tension and the compressive strength is approximately estimated by calculation.

   ii) By indirect in situ NDT or MDT, applied by specialized experienced personnel

      The following methods could be useful: Rebound test, scratch method, ultrasound measurements, penetration test, tests on new mortars reproduced in the laboratory on the basis of physicochemical analysis of the old ones or use of information on old mortars contained in specialized ancient mortars data bases.

The transformation of the above measurements and information into approximate compressive strength values could be achieved with the use of reliable bibliography. Nevertheless, their calibration would be necessary using materials similar to the existing ones in situ.

e) On the basis of all the above data, i.e.:

- The nature of blocks (stones, bricks),
- The structural category of the masonry
- The width of mortar joints
- The resistance of blocks and mortars,

The use of reliable empirical relationships existing in the literature, eventually adequately modified in order to take into account the t o t a l i t y of the aforementioned data.

In other words, it is not recommended to use empirical expressions, which take into account a small part of the above characteristic variables or situations of the masonry. More specifically, these empirical relationships must concern s e p a r a t e l y the one-leaf masonry or the two/three-leave one or the masonry of byzantine type.

[The final regulatory document will include suggestions for such empirical expressions, eventually with their necessary modifications, so that other essential parameters which are not clearly mentioned in those expressions can be taken into account].

f) The possible presence of masonry horizontal “reinforcements” (internal or external wooden beams or monolithic cornices of sufficient length etc) has to be taken into account separately by calculations.

[Relevant methods would be proposed by the final regulatory document].

(B) In situ semi-destructive tests for strength determination

a) In some Monuments of lower importance, it may be allowed to complement the semi-analytical method, by means of in situ strength determinations. To this end, flat-jacks are inserted into appropriately deep horizontal slots, so that an in situ masonry “specimen” is shaped and tested.

In the final regulatory document, a description of the relevant instrumentation and guidelines for the adequate application testing methodology and processing of data may be included.

b) Moreover, in specific cases in which partial destruction of the masonry may be allowed, the transportation of a part of the wall to the laboratory and its mechanical testing could be an option.

(C) In Lab testing of masonry replicas (models)

In the case of Monuments of higher importance, -provided that the experimental investigations described in §§1α, 1β.a have offered sufficient information-, a reproduction in laboratory (in natural scale) of a part of a critical area of the masonry under examination is suggested. These models (replicas) of masonry will be built according to the geometry of the external and internal leaf of the existing old masonry, using blocks and mortars of almost the same strength of those existing one. In case of a three-leave masonry, special care has to be given to the percentage of the voids of the filling material and the nature of its constituents. Thus, specimens will be available—replicas of the actual wall, to be subsequently tested under vertical and diagonal compression. The dimensions of these replicas should be large enough, for the failure mechanism to be freely developed.

(D) The moment/rotation relationship of the end section of a wall element

a) Pier

In case the correlation of M / θ is necessary for the analysis, it is recommended to take also into account the following:

- The angle of rotation due to M it is calculated separately from the angle due to V.
- Moreover, in case of neutral zone in the basis of the wall, the stress in the most compressed fibre of the section is not a linear function of the bending moment; thus, the "M-θ" relationship subsequently the relation of «θ» to «M», is not constant.
- When the compressive strength of masonry is reached, the available angle of rotation of the compressed zone is reduced, due to the fact that the point of zero stress is under a residual deformation even under monotonic loading.

b) Spandrel beam elements (height «h», length «ℓ», width «t»)

This plate element, fixed in both edges (without normal force), is under antisymmetric loading (M, V). As the tensioned zone is cracked along the vertical end-sections of the element, the resisting bending moment is realized thanks to an eccentric compressive force F=M:z, where "z" denoted the lever arm between the F to the left and the F to the right end section of the spandrel beam.

The horizontal force F together with the vertical V=2M:l («l» = the length of the spandrel), create a diagonal compressive force P. The deformation of the diagonal strut, will form the rotation «θ» of the horizontal «chord» of the sprandel beam.

It is noted that the positions of the forces F are determined by the effective width «b» of the compressed diagonal.

3.1.1.2. Tensile strength perpendicular and parallel to the layers of masonry

(1) The tensile strength of horizontal section (detachment strength) is equal to a percentage of the tensile strength of the construction mortar. This percentage is function of:

- the pre-compression of the joint,
- the curing conditions during the construction,
  and
- the cycles of drying/wetting of the interior of the joint (if applicable).

[The final Regulatory document will include figures for this percentage under specific conditions](2).The tensile strength of a vertical section of masonry depends significantly on the intensity and the form of the field of tensile stresses.
[The final Regulatory document will give more practical guidelines on the issue].

1.1.1.3 Strength and deformability under inclined (oblique) forces

a) The reduced strength, f_c, and the maximum deformation, ε_{cu}, of a masonry wall under diagonal compression (in presence of transverse tension) may be calculated using a reduction coefficient equal to 0,6.

The corresponding diagonal crack is considered to occur approximately when the mean perpendicular tensile stress becomes equal to a percentage of the compressive strength ranging from 1/10 to 1/20 for low and high compressive strengths, respectively.

b) The strength of a cut block under diagonal compression has to be determined in the laboratory.

3.1.1.4. Resistance of the Connection of perpendicular walls.

Possible kinematic events have to be identified, for a rational estimation of the resistance of a connection between two perpendicular walls to be reached.
The regulatory document will give practical guidelines for addressing such possible ruptures, as a function of the geometry and the degree of connection of perpendicular walls.

3.1.2. Resistances of strengthened masonry.

3.1.2.1 The effect of ties on the strength

i. Existing timber ties
ii. Added tie-beams

3.1.2.2. The effect of confinement of piers or columns on their resistance.

3.1.2.3 The effect of external ties

3.1.2.4 The effect of grouting

3.1.2.5 The effect of deep re-pointing

[These issues of important technical and scientific significance, will be treated in detail, within the final text of the regulatory document].

3.1.3 Out of plane resistances of masonry

[For all possible types of out of plane failures, the final regulatory document will provide guidance for the calculation of relevant resistances.]

3.1.4 Resistance of structures made of dry masonry (cut stones without mortar)

3.1.4.1 Strength and deformability of blocks

Special care must be given to the detailed geological and petrographic identification of the stones. On this basis, a first estimation of the range of their mechanical characteristics can be found in the literature. Additionally, in most cases the strength and deformability of blocks can be determined in the lab on specimens prepared using pieces of the same stone found in the surrounding area or taken by the same quarry or other locations having the same type of stones.

The Designer will decide for the selection of representative specimens in comparison with the stones used in the monument, taking into account the anisotropy and the ageing of materials.

Adequate tests are selected for the estimation of the following mechanical characteristics in the lab:

1 Unconfined Compressive strength

2 Tensile strength [direct tension, indirect tension (Brasilian test), bending]

3 Deformability (Modulus of Elasticity, Poisson's Coefficient)

Constitutive lows of sliding /friction.

3.4.2 Strength and deformability of walls with cut stones

Taking into account the absence of mortar, the strength and deformability of this type of walls depends on:

- The strength of blocks
- The type of wall construction

- The interlocking of blocks
- The friction on the contact surfaces
- The presence of metallic connecting elements, usually having various forms

3.5 Resistances to physicochemical actions

Taking into consideration the impact of environmental conditions on the durability of construction materials and, hence, on their mechanical characteristics, this important question will be developed in the final regulatory document.

4. SELECTION OF DESIGN SEISMIC ACTION FOR THE REDESIGN

It is recommended that the following steps are taken to select the seismic action for redesign:

1. The response of the monument to past earthquakes. In case of a damaged structure due to a recent earthquake, the action that caused the damages may be the first choice.
2. The type of the soil and the foundation.
3. The seismic action may be estimated on the basis of modern seismological theories:
    - Characteristics of the action (α, υ, T_m , etc)
    - In case of a very important monument, the action may be modified:
  - Taking into account local soil dynamic conditions
  - By means of corrections due to geomorphology
  - By means of estimation of the duration of the earthquake.
4. The seismic action will be defined considering monumentic and social values.

   a) It is reminded the contradiction between:
      - Monumentic values
      - Social values

   and the (unavoidable) search for **optimization**.

   b) The acceptable damage level of the monument (I<II<III) under the design earthquake is taken into account, in relation to
      - the Importance of the Monument (I1>I2>I3) and
      - the Visitability (V1>V2>V3)

	V1	V2	V3
I1	I	II	II
I2	I	II	III
I3	II	III	IV

   c) In relation to the permissible damage grade and the data of sections 1, 2 and 3 the following are selected:
      - The acceptable probability of exceedance (P) of the seismic action

- The level of possible local ductility (m) of structural elements of the monument (for damage > I)

Thus, the seismic action may be E_o selected.

a	**Acceptable damage level**	**I**	**II**	**III**	**IV**
b	**Acceptable probability of exceedance of the seismic action**	$P_1 <$	$P_2 <$	$P_3 <$	**P4**
c	**Design seismic action**	$E_{o1} >$	$E_{o2} >$	$E_{o3} >$	E_{o4}

5. **Preliminary design**: Based on previous experience and the index λ=R/S (see 2.4.1), the empirically selected scheme of structural interventions is dimensioned under both the normal loads and the selected seismic action E_o.

6. The effects of this seismic action on the **Momentic values** are evaluated for the selected E_o.

A1: The value of the Form (exterior/interior)

A2: The historical Value (symbolism, function)

A3: The technical Value (materials, structural techniques)

Minimum acceptable values are determined for each of the values. Every solution leading to values smaller than the predetermined $A_{min,i}$ is rejected.

For the same E_o, the following **Social Values** must be simultaneously fulfilled:

A4: the Economic Value

A5: the value of a possible New Use

The **efficiency index** of the selected scheme of interventions may be estimated:

$$\Delta = E_0 \times \sum_{i=1}^{5} f_i \times \left(A_i - A_{min,i}\right)$$

In which f_i is a participation factor for each Value, whereas

$$\sum f_i = 1$$

7. The E_o-ΔE and E_o+ΔE (with ΔEy1/3 E_o) are checked and the action with the greater Δ is picked.
8. A review of the solution from the technical point of view will then be performed.

5. CRITERIA FOR THE SELECTION OF THE MOST APPROPRIATE SCHEME OF STRUCTURAL INTERVENTIONS

The following steps should be taken for the selection of the most adequate technical solution of repair or strengthening:

1. It is reminded that the Preliminary Design (taking into account assumed values of the seismic action) was performed on a scheme of interventions that was selected on the basis of previous experience and taking into account the coefficients of inadequacy (ratio between action and resistance) of the structural members. Subsequently, the optimization process has led to one value of the design seismic action, E_d.

2. Now that the scheme of interventions is dimensioned for that design seismic action, the adequacy of the preliminary technical solution has to be further investigated. Such an investigation is necessary, since up to now, the solution is examined only in respect with the various "values" (monumentic and social). It has, however, to be assessed also from the technical point of view, i.e. in terms of compliance with the performances the selected solution may ensure, namely:

   – Reversibility/re-interventionality

   – Durability (in-time behaviour)

   – Feasibility of the proposed solution

3. Thus, an index, δ, of technical-economic adequacy of the intervention scheme has to be calculated.

4. Subsequently, various alternatives of the scheme of interventions (more or less radical) are examined. For each of them, the index, δ, is calculated. The alternative with the higher "δ" value is retained.

5. If, however, the finally selected scheme (on the basis of technical criteria) is significantly different from the initial one, we have to go back to the criteria related to the Values and check again whether the scheme of interventions is acceptable.