Title: **GUIDELINES FOR THE CONSERVATION OF HISTORICAL MASONRY STRUCTURES IN SEISMIC AREAS**

Date: August 2006

Asia-wide Programme: EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME

Project Title: IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS

Project Contract N°: ALA/95/23/2003/077-122

Project Beneficiary: UNIVERSIDADE DO MINHO, PORTUGAL

Partners: TECHNICAL UNIVERSITY OF CATALONIA, SPAIN

CENTRAL BUILDING RESEARCH INSTITUTE, INDIA

UNIVERSITÁ DEGLI STUDI DI PADOVA, ITALY

CONTENTS

1 INTRODUCTION

The research carried out within the project “Improving the seismic resistance of cultural heritage buildings” (contract ALA/95/23/2003/077-122), funded by the EU-India Cross-Cultural Programme, has included experimental and analytical study of four historical constructions of prime importance in Europe and India, namely Monastery of Jerónimos in Lisbon, Cathedral of Majorca, Cathedral of Reggio Emilia and Qutb Minar in New Delhi. The Project has lead to the proposal of a set of possible interventions oriented to preserve or upgrade the seismic response of such buildings.

Preserving or upgrading the seismic response of monuments is a challenging task due to the complex phenomena involved in the response of large masonry structures. Moreover, conceiving and developing adequate upgrading techniques is an extremely delicate operation because of the need to respect the cultural values of the monuments and, particularly, their structural features. The cultural value of the architectural heritage does not only lay on the authenticity of the materials and formal features, but also lay on the structural or mechanical features and resisting mechanisms; they are to be understood and preserved as well, to the possible extent, as part of the cultural legacy – the historical but still living testimony – meant by the historical construction.

The purpose of the present guidelines is to provide end users and professionals involved in the conservation and restoration of historical structures with concepts and principles for the conservation and seismic upgrading of historical structures located in seismic areas.

These guidelines are the result of the investigations and discussions undertaken within the project to identify and define seismic interventions appropriate for historical monuments. The guidelines have been elaborating taking in mind the four case studies considered, which cover a certain variety of structural types, epochs and cultural contexts. The guidelines should be applicable as well to similar historical buildings encompassing traditional and daring masonry structures.

In addition to the experience gathered through the investigations undertook within the research project, the project team members have considered to large extent the main specifically documents dealing with the conservation and restoration of structures of architectural heritage. Therefore, the present guidelines have its main inspiration in the well-known International Charter for the Conservation and Restoration of Monuments and Sites (the Venice Charter, 1964) and the *Recommendations for the Analysis and Restoration of Historical Structures* of the *International Scientific Committee for the Analysis and Restoration of Structures of Architectural Heritage* (ISCARSAH) of ICOMOS (ISCARSAH, 2001). These principles have been officially adopted by ICOMOS in 2003.

When dealing with heritage structures, it is important to understand than codes and calculation methods oriented to modern structures may not be adequate for ancient buildings. Designing a seismic upgrading that enforces building code requirements may result in a significant cost in terms of loss of cultural heritage. Therefore, seismic upgrading should balance different considerations, among which the desired safety level, the preservation of the original material and structural features, and the level of damage acceptable in case of an earthquake. The present document attempts to provide criteria leading to optimal decisions with regard to the extent and character of the seismic upgrading and the limitation of its impact on the original structure.

The document is divided in five different sections. The second section, after the introduction, is used to present general concepts and requirements related to conservation and strengthening of historic structures, with an emphasis in those located in seismic zones. The third section is devoted to the description and discussion of possible repair and strengthening techniques applicable to masonry structures; particular attention is paid in this section to the remedial measures that, acting at a global level, can contribute to the enhancement of the seismic response of masonry historic constructions. The fourth section introduces different possible seismic upgrading strategies and attempts to provide criteria for decision taking on optimal actions to be undertaken in monuments. Finally, a closure is provided with concluding remarks.

2 CONCEPTS AND REQUIREMENTS

2.1 Scope

The purpose of the present section consists in introducing essential terms and requirements related to the conservation and restoration of ancient structures. In particular, Section 2.3 introduces concepts related to the seismic response of masonry structures.

The general requirements to be considered in the conception and design of interventions (involving either stabilization, repair or strengthening) are considered and discussed in Section 2.4. This section is based partly on the ICOMOS / ISCARSAH Recommendations for the Analysis and Restoration of Structures of the Architectural Heritage.

2.2 Structural intervention in architectural heritage

2.2.1 Stabilization

An action can be categorized as stabilization when it is aimed at stopping a deteriorating process involving structural damage or material decay. Stabilization is also applied to actions meant to prevent the partial or total collapse of a deteriorated structure.

Stabilization is typically applied to archaeological remains or structures having partially collapsed in historical times. It is also applicable to constructions suffering chemical or physical attacks causing gradual decay of the materials, or buildings having experienced significant destruction due to an extraordinary action such as earthquakes.

2.2.2 Repair

Repair involves any action undertaken to recover the initial mechanical or strength properties of a material, structural component or structural system. Repairing is applicable to cases where a structure has experienced a deterioration process having produced a partial loss of its initial performance level.

In the context of conservation of historical structures, repair is not meant to correct any historical deterioration or transformation (including those man-made) which only affects the appearance or formal integrity of the building and does not compromise its stability. Repair should be only used to improve structures having experienced severe damage actually conveying a loss of structural performance and thus causing a structural insufficiency with respect to either frequent or exceptional actions.

2.2.3 Strengthening

Strengthening involves any action providing additional strength to the structure. Strengthening may be needed to resist new loading conditions and uses, to comply with a more demanding level of structural safety, or to respond to increasing damage associated with continuous or long term processes.

Strict conservation will normally require stabilization or repair operations. Conversely, *rehabilitation* will frequently lead to strengthening operations. Rehabilitation is defined as the upgrading of a structure to comply with modern uses and standards. Rehabilitation constitutes in fact an activity substantially different to strict conservation and frequently leads to alter the structure to an extent incompatible with the restoration principles.

2.2.4 Seismic retrofit (or seismic upgrading)

Seismic retrofitting is the modification of structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes. Seismic retrofit can be achieved by means of appropriate strengthening. However, strengthening is not the only possibility to improve the seismic response of a structure, since seismic retrofit can be also achieved through alternative strategies not necessarily involving the increase of the strength. The technology and strategies applicable to the seismic retrofit of structures are introduced and discussed in Chapter 3).

2.3 Seismic behaviour of masonry structures

2.3.5 Seismic hazard

The seismic hazard in one location is defined as the ground motion expected within a given time period. The ground motion can be indicated through the value of one or more parameters measuring the earthquake in a certain zone. The most used parameter to define the shock is the maximum peak of the ground horizontal acceleration. A more strict definition of earthquake hazard is given by the probability of occurrence of a specified level of ground shaking in a specified period of time.

The calculation for seismic hazard involves different aspects. First, the regional geology and seismology is to be examined for patterns and zones of similar potential for seismicity are drawn. Each zone is given properties associated with source potential, such as the number of earthquakes per year or the maximum magnitude of earthquakes. Finally, mathematical expressions are used to evaluate a set of hazard indicators for a given earthquake magnitude and distance. The parameters normally used as indicators are the peak acceleration or the peak velocity. More sophisticated applications may require response spectral ordinates. Information from all the zones can be integrated to produce probability curves for the key ground motion parameters. The final result gives a chance of exceeding a given value over a specified amount of time.

2.3.6 Seismic vulnerability

The seismic vulnerability of a building or a group of buildings is defined as their proneness to manifest damage in occurrence of a seismic event. As for the seismic hazard, the vulnerability may be calculated in a deterministic or probabilistic way. In the probabilistic approach, structural parameters (geometry, mechanical properties of the materials) are treated as stochastic variables.

2.3.7 Seismic specific risk

Seismic risk can be defined as the probability of occurrence of a seismic demand of a certain magnitude times the probability for damage caused by that demand. The failure of the structural systems can have various consequences such us life safety issues, loss of heritage value, repair costs, loss of function.

Theoretically, risk may be expressed in terms of economic cost, loss of lives, loss of cultural heritage or environmental damage as

$$risk = hazard \times vulnerability \times cost$$

In practice, a homogeneous measurement of cost may be very difficult to attain due to the very different nature of the negative effects of earthquakes in terms of injury to individuals and casualties, loss of cultural heritage or economic cost related to repair works.

2.3.8 Energy dissipation in masonry structures

In a dynamically deforming structure, part of the kinetic energy provided to the structural system by the earthquake is dissipated as a result of frictional forces, viscous behaviour, or structural yielding. In particular, hysteresis consists of a form of energy dissipation related to inelastic deformation of a structure.

During an earthquake, a structure will amplify the base ground motion. The ground motion at the base includes the amplification caused by the soil profile. The degree of structural amplification of the ground motion at the base of the building is limited by the ability of the structural system to dissipate the energy of the earthquake ground-shaking.

In masonry, the energy is normally dissipated through friction at the mortar joint interfaces or through damage by cracking of mortar joints. Well built masonry structures, using materials not excessively weak and sufficient bond to obtain a frictional-cohesive material, can be expected to have good energy dissipation capacity because of the friction generated at the mortar-joint interface, even if a clear distinction is needed among failures involving in-plane and out-of-plane failure mechanisms.

2.3.9 Ductility of masonry structures

In the context of seismic design, the ductility of a structure or structural member is defined as the ability to dissipate energy by developing an inelastic response under high-amplitude cyclic deformations without experiencing a significant loss in load carrying capacity. Ductility is an extremely important consideration in seismic upgrading. Ductile structures can tolerate repeated cyclic deformation for the duration of ground shaking without loosing much of their load-carrying capacity, even if they are damaged during the shaking period.

Some structural materials have a post-elastic behaviour that fits the classic definition of ductility (i.e., they have a near-plastic yield zone and this behaviour is reasonably maintained under cyclic loading). This is not the case of unreinforced masonry. Under tension, unreinforced masonry, because of the poor bonding strength at the unit-mortar interface, is a brittle material (non-ductile) that tends to loose some or most of its lateral resisting capacity after the initial damage. Under shear, unreinforced masonry generally manifests a ductile behaviour and, under compression, only moderate ductility is present.

It is noted that the material behaviour is different from the structural behaviour and, in several cases, the first crack or damage does not lead to immediate collapse. Therefore, a certain ductility can be attributed to masonry structures depending on the nature of the damage and the response at the global structural level.

(1) Nature of damage. The failure of the bond at the unit mortar interface (be the unit a brick or a stone block) does not constitute a severe damage and can be easily repaired by just filling the crack with new mortar. The continuous refilling of this type of cracks after soil settlements or other possible actions has been historically a common repair or maintenance practice. If properly executed, the so-repaired structure recovers its initial material continuity and structural performance. Moreover, the structure can be re-repaired used the same procedure. Cracks affecting bricks or stone blocks are more difficult to repair but can also be treated by means of traditional/historical or modern techniques. Masonry with damaged units has been traditionally repaired by substituting the affected material by new one.

(2) Response at global structural level. Masonry structures can show a ductile response in spite of the fragile nature of their material. The response of arches or structures composed of multiple arches adequately buttressed can be considered ductile, to certain extent, due to the plastic character of the mechanisms developed by them at failure. These mechanisms are characterized by the appearance of a number of hinges enough as to convert the structure to

an unstable mechanism, which causes the failure to be normally associated to very significant deformation. Also, failure governed by in-plane shear wall mechanisms are usually ductile and featuring large deformations, be it a shear type or a rocking failure. Something similar can be said of stacked systems (columns, some load bearing wall systems) failing because of the rocking motion of the superposed components (blocks or walls). Conversely, out-of-plane wall mechanisms are mostly associated with tensile failure, exhibiting fragile responses. This can be also the case of massive structures (such as towers), mostly characterized by a brittle behaviour.

2.4 Conservation and intervention requirements

2.4.1 Scope

The design of an intervention leading to the seismic upgrading (or any other improvement) of a cultural heritage building must comply with a series or requirements. Some of these requirements – the methodological ones – are related to the method leading to the conception of the intervention and its relationship with the previous study of the building (methodological requirements). Some others refer to the features of the designed upgrading action (design requirements). The requirements here mentioned are mostly a consequence of the ISCARSAH / ICOMOS Recommendations.

Specific requirements are also considered for urgent remedial measures which, due to their urgent but provisional character, require special considerations.

Finally, a general procedure leading to the design of the intervention, resulting from the requirements mentioned, is proposed.

2.4.2 Methodological requirements

2.4.2.1 Scientific and technological base

A deep understanding of the building and its problems is needed to conceive possible and effective solutions. A deep understanding the structural effects of the intervention and the later response of the strengthened building is also needed to warrant its adequate performance in the long-term.

To attain this understanding, the intervention must be laid-out on the basis of a scientific reasoning supported by some technological effort. In particular, an objective analysis must be carried out, based on numerical or experimental techniques, allowing a reliable representation of the unstrengthened and strengthened structure. The analysis may be used to assess the construction in its present condition and also to evaluate the adequacy and efficiency of the remedial action

The hypothesis considered to conceive the intervention on the structure should be clearly stated, as well as the procedures developed to validate them empirically (numerical simulation, monitoring, experiments…).

2.4.2.2 Integrated approach and methodological consistency

The study of a historical construction consists of four subsequent phases, namely survey, diagnosis, safety evaluation and design of the intervention. Survey is aimed at gathering data on historical evidence, geometry, damage and in situ information. Diagnosis is meant to identify causes of damage and decay. Safety evaluation is aimed at determining the acceptability of safety levels by analysing the present condition of the structure and materials.

The design of the intervention must be based on a strict consideration of the conclusions stemming from diagnosis and safety evaluation. Consistent criteria, procedures and technologies should be used throughout the process. The four phases must be logically and methodologically linked. In other words, they should consistently address the causes identified in the diagnosis (the solutions should address the real cause of the problems); and they should be undertaken using similar techniques and methodological approaches. In particular, the solutions are to be validated using strategies similar and consistent to those invested in the previous study of the building and its problems (for instance, monitoring or structural analysis can be utilized during the diagnosis and also to assess the response of the strengthened structure).

If these stages are performed incorrectly, the resulting decisions might be inadequate for the building. Poor judgment may result in either conservative and therefore heavy-handed conservation measures, or insufficient ones causing inadequate safety levels.

2.4.2.3 Need for a broad and flexible approach

Codes and rules oriented to the design of (new) modern structures may not be adequate when applied to (existent) ancient structures and may lead to inappropriate strengthening operations. Codes may fail to describe the real behaviour and strength, and to really evaluate the safety of an ancient structure. Conventional evaluation procedures are exclusively or largely based on quantitative approaches; design codes may not take into consideration the qualitative evidence coming from other sources (in particularly, inspection or history). Only with the contribution of quantitative analysis, the application of the codes may fail to provide sound and reliable conclusions on the real condition of the building and the need for any intervention. This, in turn, may lead to either underestimating or overestimating the safety of the structure and, therefore, to implement inappropriate actions. In many cases, only considering quantitative results from calculations, while ignoring possible rich evidence from a survey and the building history, may lead to underestimating the real safety and to strengthening the structure to an unnecessary degree.

These limitations of the codes and conventional methods may be overcome by accepting a more general approach involving a set of complementary activities. The activities to be considered throughout the process are historical investigation, inspection, monitoring and structural analysis. Some of these (historical investigation and inspection) provide mostly qualitative information; the others (monitoring and structural analysis) provide mostly quantitative measurements.

The concurrence of these activities permits a consistent application of the scientific method. On one hand, the elaboration of a structural model to carry out quantitative analysis (be it numerical, analytical, analogical…) means the acceptance of a set of hypotheses. In a way, the structural model is the receptacle of the hypothesis on the mechanical principles governing the response of the structure (our understanding or concept of the structure). On the other hand, the empirical activities (inspection, including experiments carried out on the structure, monitoring and history, understood as an experiment occurred at true geometric and time scale) provide empirical evidence on the response of the building. The application of the scientific method results from the use of this empirical evidence for the validation or calibration of the model. By calibrating the model, the hypotheses adopted to build the model are in turn validated or reconsidered. Once calibrated, the model can be used to make predictions on the response of the building under different actions.

2.4.2.4 Role of modelling and structural analysis

Following the above sections, modelling and structural analyses are activities to be consistently considered throughout the diagnosis, safety assessment and design of intervention. In particular, the numerical models elaborated for the diagnosis and used for the safety assessment should be also utilized to model and simulate the strengthening interventions envisaged. The simulation of a strengthening intervention (and its comparison with the simulated response of the unstrengthened structure) may provide a measure of its capacity to improve the seismic response. The numerical models can be used to simulate alternative solutions and compare their different effect on the structure.

Numerical simulation provides assistance to the study by

(1) contributing to the diagnosis by the possibility of simulating the effects of past actions on the structure;

(2) allowing a quantitative measure of the response of the structure subjected to expectable seismic actions and thus contribute to the assessment of safety; and

(3) allowing the study and appraisal of possible strengthening solutions by incorporating them in the structural model.

2.4.2.5 Role of monitoring and survey.

Monitoring and survey by Non Destructive Testing (NDT) or Minor Destructive Testing (MDT) are one of the main sources of knowledge leading to the diagnosis of the structure. These activities can be also used in a later stage to assess the adequate performance of the strengthened structure in the long term.

A distinction can be made between *static monitoring*, aimed at the continuous measurement of gradually, slow-varying parameters over a long period, and *dynamic monitoring,* aimed at the intensive measurement of sudden variations caused by isolated and short-lived actions (such as micro-tremors or hurricanes), over a brief interval of time. Dynamic monitoring, consisting of sensors measuring the oscillatory response of the building during either natural environmental or forced vibration, can contribute to recognize the main dynamic properties of the structure, such as natural frequencies, vibration modes, and other.

Dynamic monitoring requires the ability to capture a very dense amount of information during a very short interval. Thousands of readings per minute (for instance, 200 readings per second) may be needed to adequately characterize the oscillation of the structure caused by an external source of vibration, and to later carry out the signal processing leading to the determination of significant dynamic properties such as the shapes of the vibration modes, frequencies and damping. High sensitivity sensors are needed when measuring natural vibrations caused by traffic, wind or micro-tremors. Fixed dynamic monitoring may provide valuable information specifically related to the response of the structure during micro-tremors or even significant earthquakes. Long-term variations of damage are also better measured by means of a fixed system left active over a long period.

The continuous capture of dynamic motion over long periods, covering several months or even years, is also plausible thanks to more recent technological developments concerning dynamic data acquisition. Modern portable instruments, equipped with large storage capacity (tens or hundreds of gigabytes), allow the capture of continuous and dense information over longer periods of time without having only to set up an activating threshold.

Dynamic monitoring provides the only way to experimentally measure parameters related to the global structural behaviour of the historical construction. However, its real contribution to a clear understanding of structural damage propagation is strongly limited due to several causes. The parameters related to the dynamic response of the structure behave always in the non-linear range (at least those of interest for damage detection) and are highly sensitive to the local or global material properties and the support conditions. Furthermore, the dynamic response of the structure may be highly influenced by the soil-structure interaction and the environmental climatic actions (in particular, the temperature). No theoretical or numerical tools are yet available to simulate such effects in an accurate way, and thus to assist in the interpretation of the influence and variation of such parameters.

However, dynamic monitoring can be very useful to carry out model calibration or sensitivity analyses, especially when combined with complementary information on other experimentally measured “static” parameters (local Young modulus, local stresses, via flat-jack measurements).

Strengthening and monitoring should be regarded as complementary activities. Monitoring may be used to limit the extent of a strengthening operation; the adequacy of the response of the structure and the maintenance of a required “safety” can be assessed via long term monitoring; monitoring will permit the detection of a unexpected inadequate behaviour and thus give the chance to implement future corrections or additional strengthening. Monitoring can be seen as part of measures integrated within a possible “incremental strategy” (see Section 4.3).

2.4.2.6 Specificity of design

Each monument is a genuine case showing peculiar construction and structural features and specific problems. Solutions can be hardly standardized and must be conceived specifically for each building. The process leading to the conception of a solution must take into account the construction, historical, physical and mechanical reality; the concept and lay-out of the intervention are to be based on a deep understanding of (1) the resisting nature of the structure and (2) the actual cause of the lesions and structural disorders. There are no general solutions applicable to a wide number of structures.

Every ancient structure constitutes a unique and genuine problem. Beyond its own material and structural features, the building is also unique because of its historical modifications, actions experienced and existing damage. General solutions or solutions extrapolated from other cases may not be valid. The intervention must be specifically designed for each building on account of its genuine structural features, history, cultural context and present condition. Furthermore, there are no general methods leading to satisfactory solutions. Not only the solution itself, but even the method used to derive it, cannot result from all-purpose strategies.

Whatever the approach used to reach an optimal solution, it must be rooted in a sound understanding of the building and its problems. The design of the intervention must be based on knowledge on the structural nature of the building, the real cause of its alterations and the need for additional safety. Knowledge on the historical significance of the building and its cultural context is necessary as well. The knowledge gained through the previous phases of the study (survey, diagnosis, safety assessment) is finally to be invested in the design of adequate strengthening or repair actions.

2.4.3 Design requirements

2.4.3.1 Respect for structural authenticity

Monuments are not only interesting because of the value of their artistic content or geometrical conception. Monuments are also interesting and valuable because they constitute a structural achievement and provide an immediate and tangible experience on past construction technologies. Structures of monuments do not only constitute a document; they are in fact living legacies which, centuries after their construction, still carry out their resisting mission and keep on enduring loads, wind and earthquakes; they are a living and persistent proof of the skills of their creators and builders.

Proper restoration of monuments must focus on preserving the original condition of the structure. If repair or strengthening works are needed, they should cause the minimum possible alteration. This is not only applicable to the geometry and materials: the authenticity of the mechanical and resisting principles governing the structural response (the nature of the structure and its resisting mechanisms) is also to be preserved to the possible extent.

2.4.3.2 Minimum impact (or minimum alteration)

Interventions causing only a reduced impact on the original structure should be preferred, provided that they are enough to warrant the required safety level. Among possible solutions, all of them providing the required level of safety, the one causing minimal alteration (the *minimum intervention*) should be preferred.

2.4.3.3 Structural safety

In conventional structures (not belonging to the cultural heritage), seismic retrofit is primarily applied to achieve public safety, with various levels of structure and material survivability determined by considerations related to the importance of the buildings, among which are: (1) Public safety, (2) structure survivability, (3) structure usability and (4) undamaged structure. The goal of *public safety* is to protect human life, ensuring that the structure will not collapse upon its occupants or passers by, and that the structure can be safely exited. Under severe seismic conditions the structure may be a total economic write-off, requiring tear-down and replacement. The goal of *structure survivability* is that the structure, while remaining safe for exit, may require extensive repair (but not replacement) before it is generally useful or considered safe for occupation. The aim of the *structure usability* is to prevent from diminishing its utility, although it may be necessary to perform extensive repair or replacement of components in preparation for the next major seismic event; this is typically the safety level required for fire fighting stations, public safety (police) command centers, and the like. In some cases, the aim of retrofit is at ensuring an *undamaged structure* with undiminished utility for its primary application; this ensures that any required repairs are only "cosmetic" - for example, minor cracks in plaster, drywall and stucco. This is the maximum acceptable level of retrofit for hospitals.

Conventionally, it is required or accepted that structures of high cultural significance should be upgraded to remain unaffected (undamaged) by possible earthquakes. It must be noted, however, that this requirement may often lead to very impacting an invasive upgrading measures causing a significant loss in terms of cultural heritage. In some cases, the cultural loss meant by the upgrading might equate or surpass that of the damage caused by the earthquake. While the requirement of structure survivability seems obvious or reasonable for cultural heritage buildings, the requirement for non-damageable structure may be excessive and lead to counter-productive actions. The extent of seismic upgrading in heritage constructions needs to be carefully considered in every individual case based on a cost-benefit analysis which takes into account the cultural losses conveyed by the upgrading itself. Chapter 4 of this document is mainly devoted to a discussion on this delicate issue.

In the case of valuable monuments, seismic upgrading leading to non-damageable structure may be also considered to reduce the material or artistic losses (ultimately, cultural losses) that the building could experience due to an earthquake.

In some cases, authenticity (respect for the original configuration and nature) and safety (enough capacity to resist possible actions) may seem in conflict. Thorough strengthening, incurring in invasive and irreversible solutions, may cause a significant loss of cultural value to the building, no matter the difficulty in objectively quantifying such loss. The need for providing safety while preserving authenticity to the greatest possible extent is one of the more relevant challenges to be faced by the professional committed to structural restoration.

2.4.3.4 Compatibility

The materials and the technical devices used for repair or strengthening must be compatible with the original ones, meaning that no undesirable side-effect should result from their physical or mechanical contact. Ancient materials should not experience any form of chemical deterioration when in contact with the new materials or with substances delivered by them (*chemical compatibility*). New materials should not experience rheological phenomena causing possible damage (such as cracking) to the existing materials (*rheological compatibility*). New materials or mechanical devices should not behave too differently from the originals when subjected to environmental thermal variations (*thermal compatibility*). Repair materials or strengthening devices must have stiffness similar to that of the original material when embedded or externally attached to the latter, again to prevent cracking or other mechanical damage due to external loading (*mechanical compatibility*). For instance, Portland cements may free salts which, after penetrating lime mortars or stone, may experience expansive crystallization and cause cracking (chemical incompatibility). Moreover, the shrinkage of Portland cement or concrete, or their thermal deformation, may cause cracks to stone or brick masonry attached to it (rheological or thermal incompatibly). A mass of very stiff repair material inserted within the existing one may cause the latter to crack or crush due to their different deformability (mechanical incompatibility).

2.4.3.5 Durability

For reasons similar to the ones provided in the previous section, the repair materials or strengthening mechanical devices must be durable. The safety of the structure can be compromised by the loss of efficiency of the strengthening. Lack of durability leading to the decay of the new material can, in turn, convey damage to the original parts.

2.4.3.6 Non-intrusiveness (non-invasivity)

Non-intrusive (or non-invasive) repair or strengthening techniques should be preferred to more invasive alternatives. They will, for obvious reasons, contribute to preserve the material integrity of the existing structures. Among possible alternatives, preference should be given to the least invasive one.

2.4.3.7 Non-obtrusiveness

Obtrusiveness refers to the quality of being undesirably noticeable.

The Venice Charter for the Conservation and Restoration of Monuments and Sites, 1964) states that "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. Additions cannot be allowed except in so far as they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings".

According to this understanding, any additional structural device included as part of a strengthening action must integrate harmoniously with the existing structure and should not cause a significant alteration of its initial aspect. It should, however, be distinguishable from the original parts or materials.

The non-obtrusive character of the intervention should not only be applied to the aesthetic or external appearance of the structure. The concept should be applied to the morphological constitution and mechanical or resisting principles governing the response of the structure. Strengthening should not obtrusively (noticeable to an undesirable extent) alter the characteristics of the structure, its composition and working principles, even if the mere appearance or aesthetics of the building is preserved.

2.4.3.8 Reversibility - removability

Whenever possible, the measures adopted should be reversible. In other words, it must be possible to dismantle them without leaving any lasting alteration or deterioration to the original material and structure. A less stiff requirement is the potential *removability* with only limited lasting deterioration or traces left on the original construction. Removability is considered by some experts as a more realistic and viable condition than full reversibility. Reversibility or removability leave open the possibility of eventually replacing the strengthening by another more adequate or effective one.

According to the ICOMOS / ISCARSAH Recommendations, any measures adopted should be reversible, where possible, to allow their removal and replacement with more suitable measures if new knowledge is acquired. Where they are not completely reversible, interventions should not compromise later interventions.

2.4.3.9 Monitorability

Finally, it must be possible to control the intervention during its execution. Measures that are impossible to control should not be allowed. Any proposal for intervention should be accompanied by a programme of monitoring and control.

2.4.3.10 Specific requirements for urgent remedial operations

In some cases, the appreciation of an intensely damaged condition in a structure after the effects of earthquakes or any other catastrophic event may lead to the implementation of an urgent remedial measure to prevent further deterioration or a possible collapse. By definition, an urgent remedial operation will be laid-out in a very short time without the possibility of carrying out detailed investigations or studies and will normally have a provisional character. A more perfect solution, more adequately adapted to the problems of the structure and more carefully designed will normally substitute the one initially implemented. Because of this provisional character, urgent remedial operations must comply with some specific conditions.

First, the requirements regarding reversibility and non-intrussiveness are to be considered in a very strict way. Urgent operations should normally avoid any form of intrusiveness and should not only be removable but even fully reversible. The removal of the provisional strengthening must be fully viable, and it must be possible to dismantle it under controllable conditions.

A viable monitorability of the provisional strengthening is of large importance. It will normally important to know whether the strengthening (for instance, a propping system) is actually working and resisting some load, and thus partly or totally relieving the original structure, or whether the strengthening has not been in fact mobilized. This will lead to very different decisions regarding the new strengthening system and the way to implement it. Possibly, auxiliary devices or propping elements may be needed to unload gradually the existing strengthening and to transfer the load to the new one. The operations involved in this process will normally require a detailed monitoring of both the original structure and the strengthening systems.

Note that, in fact, no intervention is actually “final”. To certain extent these conditions mentioned (removability, monitorability during dismantling operations, possibility of load transferring) are convenient for any intervention.

2.4.4 General procedure leading to the design of the intervention

A general procedure for upgrading masonry structures can be envisaged based on the concepts discussed in the previous sections. This procedure involves the following steps:

(1) Survey and diagnosis on the condition of the structure, based on an integrated approach involving historical research, inspection, monitoring and structural analysis.

(2) Seismic evaluation of the structure and determination of possible structural insufficiencies.

(3) Determination of needs for seismic intervention. For that purpose, a seismic upgrading strategy (ranging between partial improvement to full upgrading, see Chapter 4, is to be adopted). The needs for intervention result from the consideration of both the seismic insufficiencies of the structure and the level (or strategy) of seismic upgrading decided.

(4) Consideration of a set of alternative upgrading techniques. Structural evaluation of the upgraded structure according to each of the techniques by means of numerical calculations or computer simulations. Selection of an optimal solution as the one which, while providing the level of desired seismic improvement, causes the lesser loss of cultural heritage.

(5) Survey of the upgraded structure to appraise / evaluate its resulting performance.

3 REPAIR AND STRENGTHENING TECHNOLOGY

3.1 Introduction

A wide variety of intervention techniques can be considered for repair and seismic strengthening of masonry structures. A rough distinction can be made among the historical / traditional and the modern ones. Historical or traditional techniques employ the materials and building processes used originally for the construction and maintenance of ancient structures; their applicability and satisfactory qualities have been proven by their recurrent use across long periods of time. Modern techniques aim at efficient solutions using innovative materials and technologies.

Another possible differentiation is between interventions operating over a material or a structural level. Actions oriented to the material level aim at treating material pathologies derived from decay or poor mechanical properties of the masonry. Structural actions are normally linked to a defective design of the structure or to structural modifications carried out during its history.

Yet, another possible differentiation is between passive and active interventions. For a more detailed description of the techniques, including a discussion and examples of application, the reader is referred to the companion document on *Identification of Strengthening Strategies* produced also as part of the ALA/95/23/2003/077-122 project.

3.2 Basic actions

Generally, the effect of any repair or strengthening technique on a structural member or an entire structure can be described as a combination of a limited number of some basic actions. These basic actions are, in essence:

Material substitution. Removal and replacement of damaged material or parts of a structure. The materials used in the reconstruction may be similar to the original ones or may possess higher mechanical properties.

Structural substitution: Creation of a new structure without the dismantling of the old one; the old structure is functionally replaced (its contribution to the overall strength is cancelled) so that only the new structure is active. A partial substitution (in which the old structure keeps partially contributing) is conceivable but difficult to attain. Note that this practice is contrary to the modern understanding of conservation of heritage structures.

Enlargement. Widening of the resisting section of a member with the addition of new material. Normally, the material used has mechanical properties similar or higher (but not dramatically higher) than the original one. The purpose is to provide a larger resisting section. The added material must be connected to the original one by means of some kind of chemical, physical of mechanical link.

Reinforcement. Incorporation of new material, characterized by its high mechanical performance (for instance, steel of synthetic fibres) to the resisting section of a structural member. The new material must be adequately connected to the original one by means of chemical, physical or mechanical devices in order to ensure its contribution to the strength and stiffness of the whole system. Reinforcement conveys the conversion of the original section to a composite one including two different mechanically active materials. The new material (the reinforcement) can be placed internally, in channels or slits created on purpose, or externally, over the surfaces of the existing member.

Improvement. Increase of the mechanical properties of the resisting section by enriching it with new material (by means of injections) or by means of a high concentration of small mechanical inclusions. Improvement conveys the introduction of a new phase distributed across the section of the element (while reinforcement refers to discrete additions inserted in the element).

Confinement. Confinement consists of implementing a stiff envelope around a material volume or structural component with the purpose of constraining its lateral deformation. Confinement can result in the enhancement of the stability, stiffness and ductility of the material or component. Confinement can be implemented in a local form or in a global form. The local form refers to techniques applied to single elements (such as piers or columns) and has the effect of constraining the lateral strain and thus improving the mechanical properties of the masonry. Global confinement is applied on the entire structure and is meant to improve the overall response of the system.

Tying. Binding together different structural components (global tying) or different parts of a single member (local tying). Steel ties are the most diffuse devices dealing with global tying. A wider variety of technologies is to be found in local tying. It is noted that nailing / stitching is here considered as one type of tying.

Propping: Sustaining or supporting a structural element or an entire structure with additional elements. It is normally applied to stabilize damaged structures as part of an emergency action. It can be also used to increase the capacity of structural members by shortening their working span. The main distinction has to be made between lateral propping (strutting) and vertical propping.

Anchoring: fastening an element or a part of a structure to a external and firmer solid. The most diffuse form is anchoring to rock and soil. This intervention is used to improve the stability of a structure.

Prestressing: Introducing a set of initial stresses by means of an artificial and controllable procedure. A common application consists of providing initial precompression to concrete or masonry structures meant to experience tensile stresses under the effect of gravity or other external actions. Prestressing is normally provided by means of prestressing tendons or bars (Note that precompression can provide additional effects different to the one here defined. A possible example is found in the possibility of tying by compression, where the tying is achieved by means of the friction caused in the interface where two different parts meet).

3.3 Repair materials

Repair materials should respect the requirements mentioned in Section 2.4.3, with emphasis in the compatibility (chemical, physical, mechanical…) with the original materials and their durability.

Ancient or traditional materials mortars, such as lime mortar, have already proven their durability and compatibility with other historical materials across long periods of time. Generally, the use of traditional repair materials is preferable because of their proven durability and compatibility with historical materials, including historical mortars, stones or clay bricks.

Modern materials have in some cases shown very important durability and compatibility problems. Iron and carbon steel can easily experience corrosion, which may lead to the loss of its reinforcing capacity (if used as part of a strengthening device); it turn, the expansive nature of the product of corrosion can generate severe damage (cracking) or even destruction to embedding or confining historical material. Mortar and concrete including Portland cement shown significant compatibility problems when in contact with original stone or brick masonries; these compatibility problems encompass chemical phenomena (for instance, the contamination of the original stone or brick with soluble salts delivered by the Portland cement, whose crystallization is expansive) as well as hygrothermal or mechanical phenomena, all frequently leading to cracking or other forms of deterioration in the original components of the masonry. Reinforced injections using steel bars have also produced damaging side effects in many reinforced monuments because of the corrosion of the steel. For these reasons, several modern application use stainless steel, namely AISI type 316, which exhibits superior resistance to corrosion.

Among metals, also titanium has recently experienced an increased utilization for repair or strengthening purposes thanks to the fact that the industrial development is making it more available and less costly.

Epoxy resins have shown in many cases very significant durability problems due to an inadequate preparation or application; in any case, a sound and definite experience on its actual durability and the durability of the bond to the original substrate is still lacking. Epoxy resins have also caused significant compatibility problems, when used as injections, due to the drastic reduction of the permeability and natural perspiration of the original materials.

Some modern materials, such as fibre reinforced polymer (FRP) laminates and sheets, show promising applications to the repair and strengthening of masonry structural components. The problem of these materials is again in the lack of enough knowledge or experience on their actual durability. Their use in rehabilitation or restoration of masonry structures is relatively recent and time has not yet given the opportunity to appraise their adequate endurance in the long term.

3.4 Traditional and historical devices and techniques

The present section includes a brief discussion on the more recurrent traditional or historical techniques used for repair or strengthening of masonry structures. Any repair or strengthening techniques will normally involve one or more of the basic actions described in Section 3.2.

Local reconstruction. The existing masonry pattern is locally removed where major deterioration has occurred and it is replaced with new masonry reproducing closely the mechanical properties of the original one. Contributes to preserving the mechanical efficiency and regaining the continuity in a masonry structure. Local reconstruction constitutes a historical / traditional technique and can be considered partially reversible.

Repointing. Partial removal and substitution of deteriorate mortar in bed joints with new mortar (possibly with better mechanical properties and durability). Repointing can be considered partially reversible and consistent with traditional / historical maintenance or repair practices.

Tie bars. Steel bars anchored with plates or other devices to the structure. They are working in tension and have different practical applications all aiming at stabilizing or improving the connectivity between parts or subsystems of the structure. Tie bars are used to improve the overall structural behaviour by ensuring seismic cooperation between structural elements. Tie bars are non-invasive and can be easily removed. Moreover, they are normally very efficient in their tying action (provided that their anchorage is maintained in good condition).

Local tying (**including cramping)**. Fastening of confining parts with different devices (pins, cramps). Local tying is meant to developing a micro-continuity in the structure thus improving structural connectivity and strength. Traditionally, cramping seems to require maintenance as the anchors tend to lose their efficiency in the medium or long term.

Element substitution. Overall substitution of a structural member. The materials and technologies used can be similar to the original ones or, else, alternative (modern) solutions can be used to modify the behaviour and mechanical properties of the structural member. A typical example is the substitution of floors and roofs. The aim is normally at recovering the original function of the element, at correcting possible design defects or modifying the seismic response. In the framework of conservation of historical monuments it is generally agreed that repair, where possible, is preferable to substitution. If substitution is needed due to severe deterioration, the use of traditional techniques and materials is preferable to the use of modern ones and to the substitution of the original parts by new elements showing a different nature and different properties.

Dismantling and reassembling. Complete dismantling of an element or a structure to repair, extract or substitute part of the components and successive remounting reproducing in detail the original organization and shape. The purpose is to recover the functionality of a structure while maintaining its historical and cultural value. According to the ICOMOS / ISCARSAH Recommendations, dismantling and reassembly should only be undertaken when required by the nature of the materials and structure and/or when conservation by other means is more damaging.

Discrete confinement in piers. Application of steel rings in critical sections of the pier with the aim of obtaining a localized confinement where needed and thus improving the compressive strength, stiffness and ductility of the pier. It is applicable to piers subjected to excessively high compressive stresses. It is a fully historical and traditional, non-invasive and reversible technique characterized by high effectiveness. It must be noted that, even if this intervention may be important to ensure the strength of piers and columns, it may have a limited effect on the overall seismic strength of a large structure supported not only by piers but also on walls and buttresses. Most of the seismic forces will normally be resisted by the side walls and the buttresses, and the strengthening of the piers will have a very limited effect on the overall seismic strength.

Discrete confinement in walls. Application of punctual confinement to the wall, either with transversal steel bars, anchored to plates or other steel devices at both sides of the wall, or with reinforced concrete elements cast in transversal holes drilled through the whole thickness of the wall The technique prevents the separation between different layers of the stone or material, thus improving the mechanical properties of the wall. It is also useful to improve multi-leaf masonry walls with no sufficient connection between different wythes. If the holes are not injected or are injected confined to a socket, the technique can be considered mostly non-invasive and reversible.

Enlargement. Enlargement of the sections of structural members by the addition of new material compatible with the original one and well connected to it. The aim of enlargement is at distributing the load to a larger resisting section, thus reducing the intensity of the stresses carried by the masonry elements. The reversibility of the technique will depend on the possibility of dismantling the added parts without causing harm to the original material.

Butressing. Addition of massive elements made of concrete or masonry to prop a structure on a side. Buttresses resist lateral forces and deformations essentially with their weight. The role of buttresses consists of impeding failure mechanisms related with lateral deformations, by carrying horizontal forces. Buttressing may be useful for structures having a low resistance to lateral forces or motion, such as arches or vaults experiencing span increase. It must be noted that, while buttresses originally built as part of the entire construction may be very efficient, similar elements added after the construction, once the structure (in particular, the original walls) are already loaded, may show very limited efficiency. This is due to the fact that buttresses built as reinforcing elements after the construction of the building will not benefit from receiving part of the vertical load of vaults and roofs, already taken by the walls, which will limit their capacity to counteract lateral forces. Furthermore, the structure will need to deform to a significant extent in order to mobilise the new buttress. The separation of later added buttresses from the walls of the building due to differential soil settlements is not uncommon.

Strutting. Placing struts between different parts of the structure or between the structure and an external system. Struts are members designed to resist a compressive load and are used to laterally prop a structure or structural member. Struts can work in horizontal, vertical or inclined position. Strutting can be used to stabilize damaged structures or elements risking collapse, or not able to carry out their load-bearing function. Inclined struts increase the lateral stiffness of the structure and are used to counteract the out-of-plane forces. Horizontal struts consisting of stone arches or timber beams are not uncommon as traditional or historical stabilizing elements. Vertical struts (props) carrying vertical load and thus discharging the original structure are normally used as provisional stabilizing elements, even if it is not unusual to find additional masonry columns added as permanent traditional strengthening technique. Struts can be considered non-invasive and fully reversible.

Filling openings. Filling part of the openings of windows and doors in façades and inner load bearing or shear walls with additional masonry fabric. Openings fill can produce a significant increase of the stiffness and strength of the structure. However, the operation means a reduction of functionality and aesthetics of the building. It is very important to not only fill openings in a single wall or part of the structure to preserve a homogeneous distribution of stiffness in order to ascertain a satisfactory seismic response. Filling openings with additional masonry can be considered a non-invasive and removable operation. To make this intervention effective, it is necessary to provide structural continuity between the masonry fabric of the perimeter of the opening and the new material.

3.5 Modern and innovative devices and techniques

Modern and innovative devices lack in some cases enough experience as to validate their effectiveness, mechanical compatibility with the original structure and fabrics, and durability in the long term. However, they provide an interesting collection of new technical possibilities. They should be used, preferably, when the traditional or historical techniques are not applicable or do not provide the level of desired seismic upgrading. Their use requires a detailed study of the possible side-effects on the original structure and materials. Modern strengthening techniques also involve one or more of the basic actions described in Section 3.2.

Injection. Injection of fluid mortar (or resin) through cracks or holes previously drilled. The purpose is to fill existing cavities and internal voids, and to seal cracks. Injection provides an improving effect and contributes to increase the average mechanical properties of masonry. Injection is a fully non-reversible operation and should only be carried out using injected materials with proven compatibility with the original material. In general, injections in historical masonry components should utilize lime micro-mortar as injected material, since it can be considered more compatible from a mechanical and chemical point of view with the original fabric.

External reinforcement. Application of high-performance materials (i.e. FRP laminates or sheets, steel mesh, wood, polymer grid and others) on the external surface of a structural element, locally or globally. The connection with the substrate is normally obtained with the use of epoxy resins, mortar and fasteners. An effective use of this technique by bonding requires some regularity in the masonry surface. In the case of seismic strengthening, it seems necessary to place external reinforcement on opposite sides and to properly connect both sides with ties. Reinforcement enhances the strength and stiffness of the structure by adding a material that can resist tension. In several cases also ductility can be increased. External reinforcement is normally irreversible and non-viable if the wall's surface has to be preserved (painted or frescoed), but non- or moderately invasive.

Reinforced injections (stitching). Holes are drilled in the element and filled with bars composed of adequate and durable metals (stainless steel, titanium…) or FRP's. The holes are usually injected or filled with fluid mortar or grout. Stitching acts by improving or reinforcing the material or structural member. Reinforced injections will cause some deterioration to the wall or stone in which the drilling is executed and, in principle, should not be applied when the walls or stones with fixed artistic contents (paintings, carving, artistic treatments or decorations). Lime mortar should be preferably used for reinforced injections. The use of Portland cement grout should normally be disregarded because of incompatibility with the surrounding stone or masonry. Reinforced injections constitute an invasive and irreversible technique, unless if a socket is used to confine the injection material. It is noted that this intervention should be only considered if other solutions are not viable not only due to its invasive character but also because of its uncertain effectiveness, especially in case of walls composed by unconnected layers.

Stitching may have inadequate side effects due to the fact that, while improving the overall strength and ductility of the member, it may also increase the likeliness of cracking and damaging in the units (stones or bricks) due to soil settlements, earthquakes or other actions. Without reinforced injections, crack wick more likely develop along mortar-unit interfaces and thus cause less significant and more easily reparable damage (see Section 2.3.9). Under moderate actions, unreinforced masonry will experience cracks, but they will mostly develop along mortar joints and will not affect the bricks or stone blocks. This type of cracks is, in principle, not difficult to repair. However, stitching will prevent this type of response; similar actions will cause also damage (cracks, local crushing) to the bricks and stone blocks; the damage will appear in a more general and distributed way and will result in a more deeply and densely damaged structure, causing a sort of less repairable lesions. This side effect can result in an undesirable loss of cultural heritage material. Nevertheless, stitching is a useful technique in several situations.

Reinforced repointing. Partial removal and substitution of deteriorate mortar in bed joints with new mortar with embedded reinforcing bars. The reinforcement is normally made of ductile and durable metals or FRP's. Reinforced repointing is indicated for masonry walls with regular horizontal joints and consists of laying reinforcement bars in the mortar matrix. It is usually applied in combination with other interventions. Reinforced repointing has been used to improve the ductility of masonry structures under heavy sustained loading.

Structural substitution. Creation of a new structure substituting structurally the old one, which is not dismantled. The purpose is to provide the structural role through a parallel or secondary subsystem, while the original one preserves its historical and aesthetical values. In principle, this type of operation does not comply with the modern understanding of conservation or upgrading of cultural heritage structures. However, structural substitution may be designed to ensure full reversibility and non-invasivity and can be considered as an extreme possibility for very severely damaged or seismically weak structures whose upgrading by other means would require the use of other more invasive and transforming procedures.

Concrete jacketing Application of self-supporting reinforced concrete cover surrounding the structural element. It is applied to elements subjected to excessively high compressive stresses, excessive lateral deformation or formed by parts poorly connected. The target is to obtain a continuous confinement and thus improving the strength and stiffness of the masonry. The jacketing can also act as enlargement (i.e. it can provide additional resisting section). Due to the need to connect the original and the added wythes or parts, jacketing can be hardly reversible. On the other hand, jacketing is obtrusive since it requires hiding the original masonry and paraments behind the new material. It is noted that the effectiveness of the intervention can be guaranteed only when jacketing is applied on both sides of the wall, with diffuse connections. The significant increase in terms of stiffness provided to the walls strengthened has to be taken into account in the calculations, since it may considerably affect the global seismic loads distribution.

Edge beams. Providing a ring of beams at the roof of floors level. Important details are the connection with the roof/floor beams and the existing walls. The beams can be obtained by casting reinforced concrete in the thickness of the existing masonry wall. Other (and more preferable) solutions are a reinforced masonry edge-beam ring (at the roof level) or a steel profile edge beam (with an internal profile diffusely connected to the external face of the wall by means of mechanical connectors or with two facing plates in the internal and external faces of the wall linked to each other by means of mechanical connectors) at the roof or floors level. The aim is to improve the connectivity between the different subsystems (walls, floor slabs, roof system). The technique is applicable to masonry buildings with poor connections between intersecting walls and reduces the risk of out-of-plane seismic mechanisms. Rather poor performance of the floors reinforced concrete edge beams solution has been reported in several cases.

Suspension. Connection of the original structure to an upper one carrying part of the load, stabilizing and relieving the original structure from its self-weight and other possible loads. The technique is applicable to structures needing support when a sufficiently resistant superstructure already exists or can be built. In some cases, technical or aesthetical reasons may lead to suspension rather than propping by means of an artefact placed beneath.

Precompression. Providing an initial state of compressive stresses by any controllable means. A side effect is usually the increase of the stiffness of the element due to crack closure and delayed cracking upon loading. The compressive force may be supplied by means of prestressing steel bars or cables working in tension, by expansive mortars or by dead loads superimposed to the structure.

External prestressing. Generating forces at critical points by means of prestressing cables fixed to the external surfaces of the structure. External prestressing can be utilized, for instance, to counteract part of the lateral thrust produce by a vault or arch to its supporting buttresses. External presstressing can also be utilized to generate overall tying or confinement of the structure. It is fully reversible and non-invasive.

Frictional contact. Providing compressive stresses perpendicular to the contact surfaces of confining elements. Generating frictional forces across different members can be used as a way to mechanically tie the two parts. A frictional union can be generated by means of prestressing by bars or tendons embedded in the structural component or fixed to its external surfaces.

Static modification by prestressing. Virtual reduction of the span or modification of support conditions by means of presstressing tendons with adequate lay-out.

Anchoring. Anchoring an element, with steel bars passing trough it, to rock, soil or to a firmer structure. Can be used to improve the stability of the structure, or constrain possible deformations. It is invasive and non-reversible if injected.

Stabilizing devices: SMA Stabilization. Shape memory alloy devices have been used to improve the stability of certain parts during the earthquake while preventing side effects caused by a rigid connection.

Dampers. Dampers are devices specifically designed to absorb the energy of motion and thus reducing seismic demand in the structures. Dampers are normally used in high-rise buildings in seismic areas. The applicability of dampers seems very limited in masonry structures (and particularly in the ancient ones) because of their large stiffness and limited deformability.

Seismic isolation. Absorbing the seismic oscillations by means of external devices usually placed between a lower foundation and the masonry structure. Excavations are made around the foundations of the building to separate the building from the ground. A new foundation made of steel or reinforced concrete is built below the original foundation. The building is connected to the new foundation by means of layered rubber and metal isolating pads. These allow the ground to move while the building experiences a substantial reduction of the seismic action.

Seismic isolation constitutes a drastic operation which requires a significant alteration of the structure, at the level of its original foundation and involves risky operations. Moreover, the durability of the isolating pads is limited, which may require its possible substitution in the mid or long term. In the case of ancient structures, seismic isolation should be regarded as an extreme operation to be only considered if all the possible alternatives were shown insufficiently effective.

3.6 Actions at the material level or on individual structural members

Repair and strengthening may be applied at the level of the material, at the level of individual components, or at the level of the overall structure. However, seismic upgrading will normally require actions undertaken at the global structural level. Because of it, the present chapter emphasizes in forms of seismic intervention intended to modify overall structural characteristics. The reader is also referred to the companion document on *Identification of Strengthening Strategies* for information on repair and strengthening at the level of the material or individual structural members (walls, vaults, roof slabs and others).

3.7 Actions at global structural level

3.7.1 Introduction

Seismic upgrading will normally require operations involving the entire structure and meant to modify its overall properties. Among possible operations acting at a global structural level, several possibilities are discussed below, including structural substitution, overall improvement of strength, overall confinement, improvement of connectivity, improvement of monolithic nature and improvement of ductility.

3.7.2 Overall structural (functional) substitution

In cases of severe need of seismic upgrading, some structures have been subjected in the past to a partial or overall functional substitution. This operation is aimed at providing a new structure, adequately prepared to resist the earthquake, while the original one is partly or totally disregarded.

Structural substitution may lead to significant problems. The mechanical properties of the original structure and the new one (which normally will consist of a steel or concrete frame) may not be compatible. Usually, masonry elements are very stiff and the frame will only provide resistance after the masonry has cracked. Additional strengthening of the original structure may be needed in order to preserve its integrity. Moreover, this is usually a irreversible and invasive strengthening operation.

This type of operation does not comply with the criteria emanating from the Venice Chart (1964), nor is it in accordance with the wish for the preservation of the original structure stated by the ISCARSAH Recommendations (2001). Only in extreme cases, for which no better alternative can be conceived, should an operation of this kind be considered. Even in these cases, the designer is obliged to actually try to envisage possible alternative seismic upgrading strategies or strengthening techniques with the aim to reduce the intervention and preserving the authenticity of the structure to the possible extent.

3.7.3 Increase of strength

A possible way of improving the seismic performance – though by no means the only possibility – consists of increasing the strength of the different structural components to obtain an overall enhancement of the seismic response of the building. The increase of the strength of the individual components can be achieved by (1) acting on their material to increase strength and / or (2) applying the strengthening actions defined in Section 4.7 to different structural components.

It must be noted that increasing strength will normally convey a side increases of the stiffness, which in turn may result in a decrease of the fundamental period of the structure, leading to possible higher seismic loads. The two effects caused by this type of actions (increasing of strength while also increasing the seismic loads) should be analyzed in detail in order to determine the beneficial / prejudicial nature of the final effect resulting from the operation.

3.7.4 Global confinement

Confinement can be used to benefit the overall structural system. Confinement can provide different effects, including overall stability, improving overall ductility, improving overall connectivity, and other, discussed below.

Global confinement has been used in many occasions to stabilize a severely deteriorated structure in the frame of an emergency or provisional action. In this case, confinement is normally achieved by means of external devices such as steel frames or rings. Given its provisional character, these devices must be removable without causing any damage to the historical material.

Global confinement can be also implemented as a final upgrading operation. In this case, light and external elements are preferable. A light character (for instance, thin strings are better than rigid steel profiles) is desirable to improve their appearance. An adequate aesthetic treatment of the external surface, involving the selection of adequate shapes and colours, is also necessary. In some cases, the devices providing the confinement are placed in the interior or are embedded in the structural elements; as a result, the external appearance of the building is not affected but at the cost of significant invasiveness and irreversibility.

3.7.5 Improving monolithic nature

The monolithic nature of the structure is conventionally regarded as a convenient feature for modern reinforced concrete structures. The monolithic nature refers to the quality of being constructed or behaving as a single stiff piece with no joints or weak planes separating the structure into different parts. In practice, concrete structures have construction joints and weak intersections, but these are corrected by means of continuous reinforcement linking intimately the different members. The final behaviour of concrete structures actually tends to the monolithic ideal.

Masonry structures are not similarly monolithic; in fact, masonry structures are far from being monolithic both at the micro and at the macro scale. In the micro scale, the monolithic nature is compromised by the composite nature of the material and the weakness of the bond between the different components (brick or stone blocks and mortar). At macro scale, and due to the very limited tensile strength of the material, masonry structures can be easily divided into large parts (or macrolements) due to poorly or not interlocked construction joints, or cracks developed due to differential soil settlements, thermal effects or weak construction joints.

In the past, and as a result of the confidence on modern materials and technologies (concrete), improving the degree of monolithic nature was regarded as an adequate seismic upgrading strategy for masonry structures. These were made monolithic to greater extend by means of injections or reinforced injections, inserted concrete frames or other procedures. Complete underpinning of the structure was needed in many cases to ensure stiff foundation and prevent from even small differential settlements which could easily damage the strengthened structure.

As a result, the structures experienced a deep transformation and tended to develop mechanisms totally strange to the response of a true masonry structure. The gain in stiffness resulted in higher modal frequencies and increased sensitivity to earthquake. Moreover, some of the qualities of masonry structures – such as dissipation due to friction along bed joints – where lost.

The past experience on structures upgraded according to this strategy has been extremely negative. In many cases, recent earthquakes have resulted in more integral collapses or important partial destructions in comparison with similar structures free of similar interventions. Moreover, the intervention in itself is highly invasive and irreversible and means always an intrinsic loss in cultural value. In short, this type of upgrading should be normally avoided in masonry structures. Other possibilities, discussed below, should be preferred.

3.7.6 Improving connectivity

In masonry load bearing wall systems, adequate connection between the structural systems involved in the seismic response is essential to avoid collapse or poor performance during the earthquake. An adequate connection must exist between converging perpendicular walls, as well as between floor diaphragms / roofs and walls.

The adequate response of the system depends on the capacity of the diaphragms to distribute the horizontal forces among the structural walls; in addition, the forces must be adequately transferred to the walls across the intersections between the diaphragms and the walls. Furthermore, the walls must be able to mobilize their strength without experiencing lateral instability or out-of-plumbing.

Converging perpendicular walls contribute reciprocally to their stability. Floor diaphragms tied to the walls contribute as well to the stability of the latter.

The connection between perpendicular structural walls is traditionally achieved by simply interlocking bricks or block stones in corners or intersections. In the case of brick masonry, cracking along the intersection can easily occur as a result of previous soil settlements or environmental thermal effects; it can also appear due to the earthquake. Cracking in wall intersections obviously acts against the mutual stabilization of perpendicular walls.

The connection between floor diaphragms and load bearing walls has been traditionally produced as a simple direct contact between the two – the floor being simply supported over the wall. However, a simple and direct contact between these members is not adequate because it can not resist the complex forces which are generated in the connection by the earthquake; these may involve bending, shear and tension, which can hardly be transferred through a simply compressive or frictional contact. Ideally, the contact between these members requires a certain degree of interlocking or structural continuity allowing the transference of a variety of forces including bending, shear and tension.

Improving the connection between these elements will contribute very significantly to improve the seismic response of the building. It must be noted, however, that improving the connection does not necessarily require the provision of a monolithic nature to the structure; these connections can be improved by means of flexible devices which, while granting the adequate connection and stability during the earthquake, nevertheless maintain or even enhance the intrinsic ductility and dissipation capacity of masonry constructions. An elastic (flexible) connection can be obtained by means of traditional solutions such as metallic ties or anchors. Ties are normally launched across the bays of the building and are embedded in the floors or walls, or by means of metallic anchors. Forming concrete edge beams in the connections between floors and walls (a more modern and widely used solution) leads to a more stiff and monolithic structure.

The adequate functioning of the system requires the floor slabs to actually act as stiff diaphragms able to carry the horizontal forces and distribute them among the different structural walls. The historical or traditional timber floors may not be stiff enough as to actually carry this role. A widespread modern solution to improve stiffness consists of forming a thin reinforced concrete topping over the timber floor slab. This solution may provide larger stiffness than actually needed to generate the stiff diaphragm;

other less weighty and more flexible solutions can be conceived for the same purpose, such as constructing a continuous timber platform over the existing floor.

In short, the seismic performance of masonry load-bearing systems can be upgraded by improving the connectivity between the essential structural members (perpendicular walls and floor diaphragms). However, improving their connectivity does not necessarily require a significant alteration and does not necessarily convey a significant increase of the stiffness of the building. An adequate improvement of the connectivity can be achieved by means of traditional devices (anchors, ties) which, due to their flexibility, may preserve a significant part or even improve the ductility dissipation capacity of the building. Only moderate stiffness of the floor is usually necessary and the strong increase of mass using heavy slabs is not recommended.

3.7.7 Preserving / enhancing ductility

As mentioned in Section 2.3.9, masonry structures show certain ductility depending on the type of structural system. Such ductility may be significant in case of skeletal structures composed of arches, limited in the case of load bearing walls systems and very low in case of massive structures such as towers.

A significant increase of the global ductility is generally difficult to attain in masonry constructions. Rather than seeking a very significant increase of the ductility, seismic upgrading should focus in, at least, preserving or enhancing the intrinsic ductility and dissipation capacity of masonry structures.

In case of skeletal structures, the overall ductility can be improved by tying the arches or linking critical points by means of ties (tying arches may have a limited “cultural” acceptability as strengthening technique, depending on the cultural context). External prestressing may also contribute with some additional ductility.

In load bearing systems, the improvement of the connectivity by means of flexible connections, as described in the previous section, can lead to additional global ductility.

Confinement of individual elements (such as piers) or global confinement can also provide additional ductility in all kinds of masonry constructions, as in particular in massive towers.

4 SEISMIC STRENGTHENING STRATEGIES

4.1 Introduction

This section is aimed at providing criteria for the selection of adequate seismic strengthening techniques.

A discussion is included on the aspects that should be considered in the selection of possible solutions, including those involved in the seismic hazard (seismicity), the vulnerability of the building (structural design, construction quality) and the potential cost of the effects of the earthquake (cultural losses and issues related to public safety).

Based on the previous considerations, two alternative approaches aimed at determined optimal solutions are considered and discussed. The first one is based on the concept of seismic improvement. The second one constitutes a criterion for decision-taking stemming from the consideration of a level of acceptable damage.

4.2 Preliminary considerations

4.2.1 Limitations of codes and conventional calculation methods

Codes and conventional methods mostly oriented to modern constructions may fail to describe the real behaviour and strength of an ancient masonry structure and to actually evaluate its safety. Conventional evaluation procedures are exclusively or largely based on quantitative approaches; design codes may not take into consideration the qualitative evidence coming from other sources (in particularly, inspection or history). Using only quantitative analysis, the application of the codes may fail to provide sound and reliable conclusions on the real condition of the building and the need for any intervention. This, in turn, may lead to either underestimating or overestimating the safety of the structure and, therefore, to implement inappropriate actions. In many cases, only considering quantitative results from calculations, while ignoring possible rich evidence from a survey and the building history, may lead to underestimating the real safety and to strengthen the structure to a unnecessary degree. These limitations of the codes are obviously overcome by accepting the more general approach described in Section 2.4.2.

4.2.2 Applicability of seismic codes

The enforcement of codes prepared for modern constructions can lead to drastic measures resulting in a major alteration of the ancient structure with the loss of significant cultural value. This is particularly so in the case of seismic codes. This aspect is different to the one previously discussed and does not point to the validity of the method specified by the code, but to the requirements on the safety level. Enforcing seismic codes may lead to major (and economically costly) strengthening causing significant alteration and loss of cultural values. It is necessary to recognize that the application of seismic codes (not specifically addressing the case of existing structures) to historical constructions may not be viable due to both cultural and economical reasons. The implementation of the required strengthening may, in practice and in many places, lead to the real loss of an enormous amount of valuable architectural heritage. From a cultural point of view, the enforcement of codes may cause an enormous loss of cultural values; from an economical point of view, a full retrofitting of the massive amount of valuable ancient structures existing in many seismic countries (as, particularly, in the Mediterranean ones) is unaffordable. It is noted that even Eurocode 8 and FEMA recommendations, while addressing existing structures, do not contemplate architectural heritage structures.

4.2.3 Seismic improvement

Conversely, ignoring the requirements and accepting a reduced safety level may lead to a larger risk for human beings. This may seem not acceptable in principle, being the need to provide adequately safe conditions to possible users or visitors non-negotiable. However, the full application of conventional seismic codes to ancient structures is just unrealistic and other possibilities are to be envisaged.

The main problem of accepting a lower level of safety does not lay exclusively in the risk of further damage or destruction, or loss of movable heritage stored in the building, but mostly the loss of human lives. This aspect poses a very difficult problem – an inherent conflict – between true conservation and safety. Difficult decisions have to be taken which may exceed the competence of the designer and may require the concurrence and complicity of the authorities. Measures involving restrictions on the use of the building or the number of visitors can be also considered as an alternative to excessive intervention.

Seismic “improvement” of existing buildings, as introduced in the Italian seismic codes since 1986 (D.M. 24/01/1986) and expressly related to “monumental buildings” since 1996 (D.M. 16/01/1996, O.P.C.M. 3431/2005) provides a possible way of confronting this difficult dilemma. The recognition of the possibility of “improvement” offers a legal framework for the acceptance and implementation of possible solutions which, while not causing significant losses of architectural value, nevertheless provide a significant enhancement of the seismic response of the building.

The Italian seismic code accepts the possibility of not necessarily providing to an existing building the same seismic upgrading level that would be required for a modern or new building. In some cases, it is accepted to apply a partial seismic “improvement”, that is to say, to provide an improved safety and seismic response through a certain level of upgrading. For seismic “improvement” to be acceptable it must be shown that the works to be carried out on the structure will actually cause an increased degree of safety towards earthquake. The concept is applicable, in particular, to existing buildings belonging to the architectural heritage.

Even if partial seismic improvement is acceptable, existing structures are to be analyzed in detail (in terms of local seismicity and seismic structural performance). A clear understanding of their seismic insufficiency and possible strengthening needs must be attained in any case. The effect of the partial seismic improvement on the seismic performance must be accurately characterized and quantified. In the case of important monuments, partial seismic improvement should be only accepted on the basis of a clear understanding of the seismic performance of the structure before and after the intervention. A clear understanding of the response (and remaining insufficiency) of the partially improved structure, and a clear vision of its resulting vulnerability and possible risks meant to people, are to be reached and, if possible, even quantified as an increase of the safety factor of the structure..

4.2.4 Need for seismic upgrading

Seismic upgrading requires the consideration of different aspects related to the structure and the seismic demand. Generally, the level of seismic upgrading required will increase with the seismicity, the possible insufficiencies of the original structural design of the building, the state of conservation of the structure and the intensity of the use allocated to the building. These aspects are discussed below:

Local seismicity. The need for seismic upgrading is obviously connected to the local seismicity of the location. It must be noted that even in areas of moderate seismicity, historical constructions may require some seismic upgrading due to their intrinsic weakness or structural insufficiency.

Structural design of the building and resulting seismic response. The structural design, including the structural arrangement and the construction and morphological qualities of the building, will determine its seismic response. It must be noted that some structures may show a limited seismic capacity due to inadequate aspects related to their structural design, or to construction or material deficiencies. In areas of low to moderate seismicity, the lack of experience on seismic response may have caused the construction of buildings with very poor seismic performance. Even in low seismicity areas, buildings may show to be very vulnerable to earthquake due to the inadequacy of their structural design.

Quality of construction. Materials and construction details influence on the seismic response to larger extent. A conveniently designed construction which, nevertheless, has been built with inadequate materials and poor construction details (poor connections between parts, poor interlocking between the units composing of the masonry) will behave in a deficient way in case of earthquake. The quality of the construction is sometimes considered as the aspect of the building with largest influence on the resulting seismic performance.

State of conservation of the structure. Historical structures may show a very different condition with regards to the extent of material decay or damage caused by previous earthquakes, long-term effects or lack of maintenance. A poorly preserved construction may experience a very significant decrease of its seismic performance with respect to that of the preserved (or theoretically intact) counterpart. This reduction on the seismic performance may be caused by cracks causing the separation of large parts of the structure, the deterioration of connections between structural members, the reduction of the sections of the structural members or the reduction of the strength of the materials.

Use of the building. The foreseen use for the building determines the number of possible users or visitors, as well as the possible valuable contents in terms of movable heritage (e.g. books, paintings, sculptures and others). Therefore, the use determines the cost in terms of injury to people and loss movable heritage of a possible earthquake. The need to avoid injuries or casualties in buildings, which normally host large amounts of users or visitors (religious buildings in use, museums), should lead to seismic upgrading preventing any kind of damage that can compromise the safety of people. A similar reasoning applies to the need of avoiding the loss of valuable movable cultural heritage. When dealing with monuments, the possibility of limiting the use (the type of use, or the number and frequency of visitors) should be also considered as a way of reducing the risk.

Cultural value. In heritage buildings, damage and destruction due to the earthquakes will also have a cost in terms of cultural value related to the immovable heritage. Firstly, this includes the costs or losses caused on the structure itself. Any loss in the integrity of its materials, structural features, geometry and performance should be regarded as a cultural cost. A second contribution to the cost is found on the possible deterioration or destruction of valuable artistic components fixed on the structure, such as architectural decoration, sculptures or mural paintings (frescoes). In some cases, the cultural value of these artistic components (the immovable contents) may be extremely high, as in the case of churches decorated with frescoes painted by important artists, and may surpass, by far, the value allocated to the structure (the container). These aspects are further discussed in Section 4.2.7.

The above aspects are all involved in the determination of the seismic risk affecting the building. Local seismicity determines the seismic hazard to which the structure is subjected, while the structural design, construction quality and state of preservation influence on the vulnerability of the building. The use and the cultural value determine the costs which can be caused by the earthquake. In turn, as shown by the equation in Section 2.3.7, the product of hazard, vulnerability and cost gives the seismic risk.

4.2.5 Cultural losses due to earthquake

As aforementioned, the cultural costs or losses include the possible damage or destruction caused on the structure (container), those caused in possible artistic heritage fixed to the structure (immovable contents) and those caused in possible movable cultural heritage located inside the buildings (movable contents). In this section only the structure and the immovable contents are considered.

Regarding the structure, any loss in the integrity of its materials, structural features, geometry and performance should be regarded as a cultural cost. The impact of earthquake on the structure may produce very different types of losses and cost amounts. These may be roughly categorized in function of the type of repair / strengthening required to stabilize the building:

(1) Low costs. Some of the effects or damage caused by the earthquake may be reparable using historical / traditional techniques related to common maintenance practices. They can be repaired without altering the resisting nature of the structure. After repair, the structure may recover its initial capacity without having experienced any significant alteration.

(2) Moderate costs. Other effects may require more sophisticate repair techniques involving materials or devices strange to the original features of the building. Among these, some effects may be reparable using non-intrusive, reversible techniques.

(3) High costs. In some cases, the effects of the earthquake may require repair or strengthening by means of intrusive or irreversible techniques

(4) Irreparable losses. Yet in some cases, the destruction produced in the building may require partial / total reconstruction or, alternatively, the acceptance of the losses or disappearances produced, with no possibility of recovering the previous construction by any repair or strengthening technique.

4.2.6 Cultural value and seismic upgrading

The costs referred in the previous section, as those caused to the safety of people, will be prevented or controlled by implementing a preventive strengthening or seismic upgrading. However, any preventive action on the building will incur always in some cost as it will inevitably cause a certain alteration on the original materials or configuration of the structure. Seismic upgrading using any of the techniques described in chapter 3, or other possible techniques, will always convey a certain alteration of the structure.

As in the previous section, the cost or cultural losses caused with the implementation of the strengthening can be roughly classified in function of the extent and nature of the operations. An upgrading based on non-invasive and reversible operations should be considered of moderate cost, while one conveying invasive or irreversible operations should be associated to a high cost.

4.2.7 Buildings with fixed artistic heritage

The case of historical structures supporting a valuable fixed artistic heritage (such as mural paintings) needs a specific treatment. The priority, in these cases, is in the conservation of the artistic heritage, which, due to its nature, is normally very delicate. Cracks or deformations in the structure due to earthquake (not to mention partial collapses) can result in significant damage to the artistic heritage (mural paintings can crack and even detach and fall down from their supporting walls). In the case of very valuable artistic immovable contents, thorough strengthening may be required to preserve its integrity even in the occurrence of an earthquake. Due to the cultural value of the contents (which in many cases can be judged to be higher than that of the structure), a certain transformation of the structure, even if significant, should be acceptable as a way to ascertain the integrity of its artistic contents. Thorough strengthening oriented to prevent the structure from experiencing significant deformation and cracking during the earthquake may be needed. Seismic “improvement” of the structure only may not be acceptable in these cases.

However, the value of the structure and the possible cost of the strengthening (in terms of cultural value and authenticity of the structure) should be also recognized and evaluated in these cases. Even if the focus is in the conservation of the immovable contents, solutions causing a limited (or at least, the lesser possible) alteration to the structure should be preferred. Among the solutions granting the conservation of the immovable contents, these causing the minimum alteration to the structure should be preferred.

4.2.8 Damaged structures and poorly preserved structures

The treatment of structures showing conservation problems (significant damage and other problems related to long-term damage processes, previous earthquakes or just lack of maintenance) requires some specific considerations.

In some cases, the repair of the structure may be enough as to provide an adequate level of seismic improvement, meaning that the repair alone may be acceptable as a strategy leading to (enough) seismic upgrading. The concept of repair here referred is the one specifically defined in Section 2.2.2.

In other cases, repairing the structure may not be enough as to recover the initial strength of the structure or to ensure an adequate seismic response. This may be the case of structures that, even in its theoretical intact configuration (previous to any damage), would show an inadequate seismic response. In these cases, additional strengthening, meant to improve the seismic response, may be necessary.

In any case, the repair of the structure must always be considered as a possible action. The structure can be just repaired, just strengthened, partially repaired and strengthened, or straightforwardly strengthened with no repair or only minor repairs. Among these possibilities, repairing (to a reasonable extent) may be preferable to strengthening in many cases. Whenever possible, interventions focusing mostly in repairing rather than in strengthening should be preferred. Straightforward strengthening without previous repairing seems less advisable unless the repair of the existing and weakening damage is very difficult or impossible.

4.3 Possible upgrading strategies

The consideration of the aspects mentioned in the previous sections should lead to the selection of a possible strengthening approach. The following upgrading strategies are here recognized:

(1) Preventive maintenance. A detailed maintenance programme is laid-out in order to ascertain the conservation of the present condition of the building in the long term. Preventive maintenance should be carried out using historical or traditional practices (refilling of mortar losses, substitution of deteriorated individual stones, …).

(2) Preventive surveillance. A monitoring programme is undertaken to gather additional information on the response of the building and to assess the maintenance of its condition in the long term.

(3) Preventive repair. In the case of damaged structures, repair may be execute to recover (partially or totally) the strength capacity of the building. The damage is repaired using traditional or historical techniques and materials. No strengthening is actually implemented. This strategy may be applicable to buildings located in low seismicity areas. It is also applicable in high seismicity areas in the case of structures showing satisfactory seismic resistant qualities. Repair may involve the recovering of the continuity across cracks or separation causing large discontinuities, local substitution of deteriorated individual blocks, unreinforced repointing or local improvements of the material strength.

(4) Light strengthening. Implementing discrete (concentrated) strengthening using light, reversible, non-invasive mechanical devices. Produces no alteration of material properties and only a limited alteration of the global structural properties. The implemented devices are mobilized only by extraordinary (horizontal) actions. Techniques are such as tying (across spans), strutting, prestressing, stabilizing by means of SMA devices. Local improvement may be also considered. The aim is to cause a perceptible improvement of the seismic response of the structure while causing only a very limited alteration of the original structure. This approach is aimed at providing the optimal solution in terms of cost-benefit analysis, the cost being the loss of cultural value, the benefit the gain in seismic resistance. In low to medium seismicity areas, the strategy may provide a very satisfactory level of seismic response. In high seismicity areas, light strengthening may in some cases provide only a partial

improvement. The acceptability of seismic “improvement” (where applicable) should lead normally or preferably to light strengthening solutions, even in high seismicity areas.

(5) Extensive strengthening, partial upgrading. Includes extensive operations affecting a large part of the building. The technologies used are distributed in a smeared (continuous) way across significant volumes or parts of the structure. The operations involved may be irreversible and invasive to significant extent. The strengthening implemented produces an alteration of the material and mechanical properties of a large number of members or of the entire structure. The structure may be forced to work in a modified way with respect to its original design and resisting mechanisms. The strengthening is also mobilized by permanent or frequent actions (gravity, wind). The techniques are such as enlargement (backfilling), reinforcing, continuous confinement, local tying, stitching, extensive improvement (injection), and might include actions at the level of the foundation (e.g. micro-piling). In the case of partial upgrading, these operations are undertaken to cause only a partial, but very significant, improvement of the seismic response.

(6) Extensive strengthening, full upgrading. Techniques similar to those mentioned in item (5) are used to achieve the safety level required by a seismic regulation for a modern building in the same location.

(7) Incremental approach. Monitoring can be taken into consideration to base an intervention on an observational (experimental) approach. Monitoring may allow the acquisition of information during a step-by-step procedure in which the behaviour is monitored at each stage and the data acquired is used to provide the basis for further action. In particular, this approach can be utilized to assess the maintenance of a sufficient level of safety in the long term. This strategy may be used to limit the intervention even in buildings showing severe problems. In better preserved structures, it can be used to assess the maintenance of safety with very limited or almost no intervention. It should be also utilized as an alternative to extensive strengthening whenever light strengthening is considered insufficient. In these cases, light strengthening, combined with preventive surveillance, can be used to assess in the long term the performance of a (lightly) strengthened structure.

4.4 Categorizing solutions

The possible ways of intervening on a structure can be classified in different categories depending on their nature and extent. These categories can be represented using a cost-benefit diagram (Figure 1). At least three different categories can be easily distinguished:

A first category (**category I**) can be considered for solutions producing only a very limited alteration of the structure. Solutions focusing on maintenance works or on the repair of damage (cracks) by traditional / historical procedures can be included within this category.

Category II involves solutions that consider possible strengthening by means of light, non-invasive (or slightly invasive) and (mostly) reversible devices, in combination with possible maintenance / repair operations to be carried out following traditional techniques. Solutions meaning only a limited invasion are included in this category. The solutions corresponding to this category should not cause a significant alteration of the strength nature and resisting mechanisms of the structure.

Category III includes solutions based on the implementation of heavy or moderately invasive and irreversible techniques (such as using embedded reinforcement or devices – profiles, reinforcement – requiring previous perforation across the historic material, or enlargement by means of material layers connected to the historical material by means of stiff connections, or physical / chemical bonding across large contact interfaces). The solutions in this category may cause a significant alteration of the strength nature of the structure and, in the extreme case, may even convey a partial or total functional substitution of the structure.

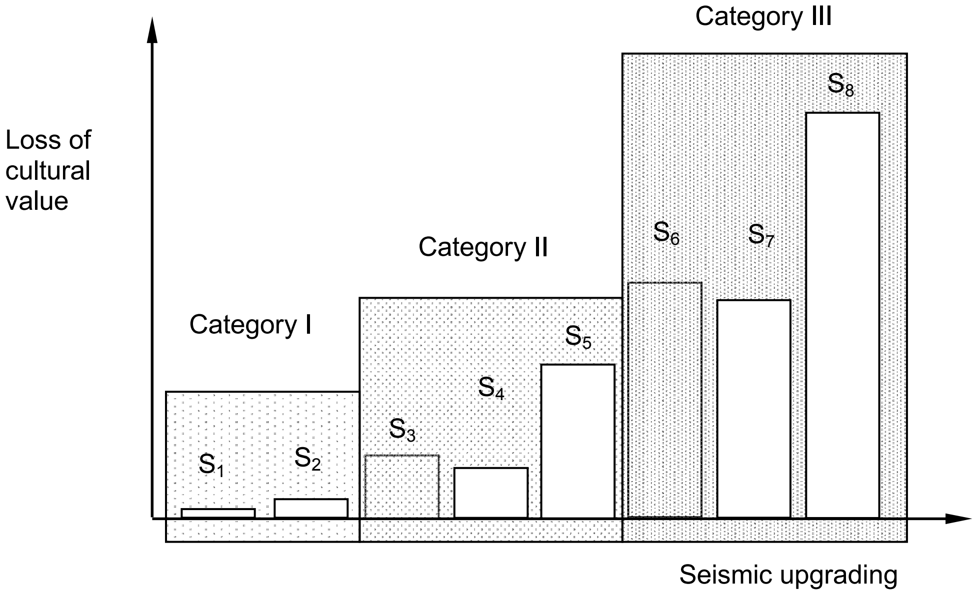

Figure 1:. Classification of possible solutions S1,…, S8 in different categories depending on the extent of the transformation caused on the structure

4.5 Selection of strategies and decision taking

4.5.1 Selection of strengthening solutions based on seismic improvement

The acceptance of the concept of improvement (Section 4.2.3) conveys the possibility of a widespread choice between possible minimal and maximal interventions. The minimal one corresponds to not actually upgrade the structure (all the operations consist on maintenance or minor repairs). The maximal one can be associated to a full upgrading of the structure to ensure its capacity to resist the earthquake with very limited damage. The earthquake to be considered for this purpose should be the one defined by the national seismic code for the location of the structure, or even higher depending on the importance of the building. The role of the designer consists of choosing a level of "improvement" contained within these two extremes.

The optimal level of improvement might be decided through the consideration of a cost-benefit analysis, where the cost is the loss of cultural value and the benefit is the improvement of the seismic response. This analysis, however, is difficult to carry out because both variables (loss of cultural value and improvement of seismic response) are difficult to quantify in an objective way. Besides, both the cultural value and the upgrading efficiency are multidimensional and complex variables which in fact can not be summarized in a single scalar parameter.

In some cases, the relationship between seismic upgrading and loss of cultural value can be presumed to vary according to Figure 2. In this case, seismic upgrading will cause null or very limited alteration (and cultural loss) up to certain point O. Until reaching the limit O, a certain improvement may be carried out at almost negligible or limited cultural loss; however, further improvement beyond limit O will cause a very significant loss.

It must be remarked that, for other structures, the diagram relating cost and benefit may show a different profile; moreover, different envisaged upgrading techniques might produce different diagram shapes.

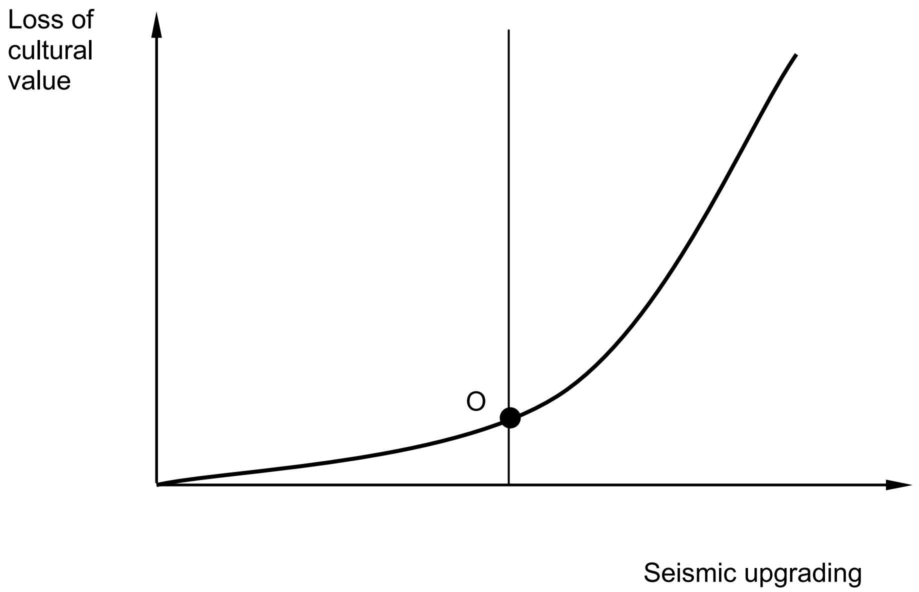

Figure 2. Possible relationship between seismic upgrading and loss of cultural value caused on the building

It seems reasonable to select a level of improvement contained within the origin and the limit O; furthermore, it seems also reasonable to prefer a level of improvement close to the limit O as a way to obtaining maximum benefit in terms of strengthening upgrading while still keeping the loss of cultural values within acceptable limits.

In practice, elaborating such an specific diagram will not be possible because of the complexity involved in the variables of the problem. Rather than thinking in a continuous way (and seeing the cost and the benefit as continuous variables), it will be more practical and realistic to consider just a limited (discrete) number of possibilities. In practice, the designer should proceed by considering a number of different possible solutions (S_1, S_2,…, S_N) based on different techniques or characterized by their different extent. For each solution, an attempt should be made to determine the improvement of the seismic response (seismic upgrading) and the loss in cultural value. By arranging the solutions according to their seismic upgrading capacity, a bar diagram similar to that of Figure 3 will be obtained.

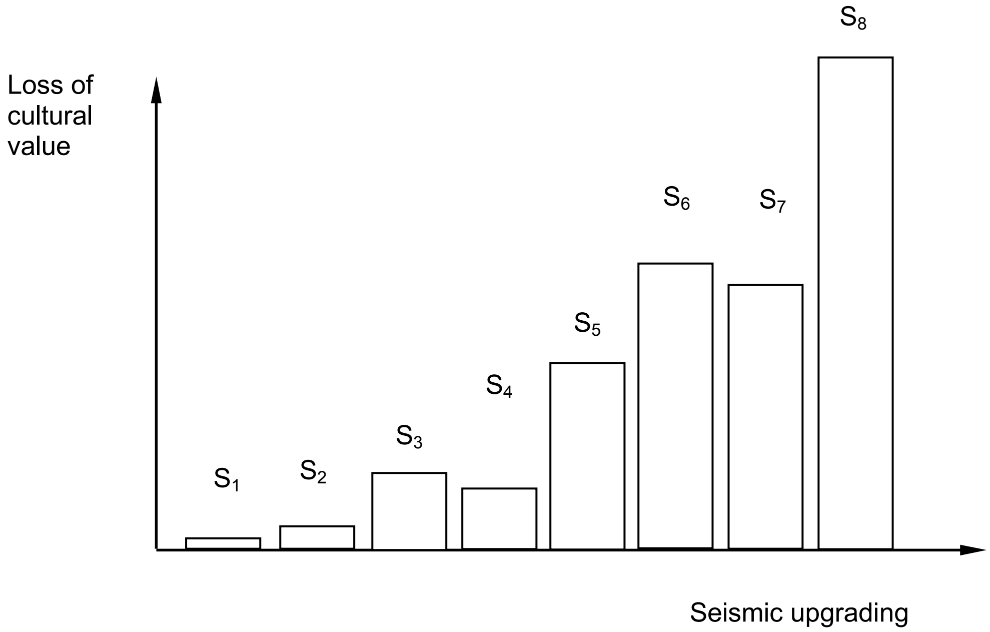

Figure 3: Loss of cultural value caused on the building by different solutions characterized by a different capacity for seismic upgrading

A diagram of this kind is useful to help determining solutions with an adequate cost/benefit ratio. In the example of Figure 3, solutions S_4 and S_7 provide higher seismic upgrading with a lower cost that other solutions. As in the case of Figure 2, the diagram helps visualizing a certain group of solutions for which significant seismic upgrading is possible at a very limited cost (solutions S_1 to S_4) and, among them, a solution producing a best relationship between benefit and cost may be also identified.

Depending on the nature of the problem, the solution producing the best benefit / cost ration may fall in one of the different categories envisaged in Section 4.4.

4.5.2 Selection of strengthening solutions based on acceptable damage

4.5.2.1 Cost evaluation

The selection of optimal upgrading solutions can be based on the minimization of the possible losses caused by the earthquake. In the case of the monuments, the losses to be included are (1) the cultural loss which may be caused by damage or destruction produced by the earthquake in the immovable heritage (structure and immovable contents) and (2) the loss that the seismic event may cause in the form of injuries to people or casualties, and in terms of cultural loss in the movable heritage stored inside the building.

The strengthening strategy to be implemented should be oriented to minimize the cost associated with both types of losses. However, these are costs of very different nature and can not be compared or included in a single variable. In the present guidelines, no attempt is made to integrate both in a single decision-taking procedure. Instead, they are considered and linked to the decision taking procedure separately as described in the following sections. In the procedure proposed the selection of strengthening strategies is based on the evaluation of the potential immovable cultural losses (Section 4.2.5). The aspects related to human safety and movable heritage are considered after the selection of a possible strengthening strategy with the purpose of validating the use intended for the building (Section 4.5.2.4).

It is important to make a clear distinction between the type of damage meant by the implementation of the strengthening and the one potentially caused by the earthquake. The strengthening will be obviously designed not to cause any deterioration to the fixed artistic heritage but may include actions of irreversible and invasive character (insertions, injections,…) on the structure. The potential damage due to the earthquake (including deformation, cracks and even partial or total collapses) can deteriorate or destroy the artistic heritage.

Both types of damage can be included into a single variable by using adequate weights. The loss of cultural value can be evaluated as

$$C = f_0 C_0 + C_e$$

where C_0 is the loss produced by the upgrading itself, while C_e is the potential loss caused by the earthquake. Factor f_0 is meant to weight the importance of the structure compared to that of the artistic heritage, and can be set up as

$$f_0 = V_e / V_a$$

where V_e and V_a are the values allocated to the structure and its immovable artistic contents, respectively.

4.5.2.2 Acceptable damage

The conventional objective of seismic upgrading of normal buildings lays mostly in public safety. Public safety is also one of the aims of the seismic upgrading of monuments. The aim is to ascertain the stability of the building during earthquake and thus preventing unacceptable risks to people. As for modern buildings, a certain degree of damage is acceptable.

Because the costs in public safety and the costs on cultural heritage, the effects to be caused by an expectable earthquake on a monument should be limited to an acceptable amount. Three different situations can be envisaged, at least, regarding the amount of acceptable damage in monuments:

(1) *Acceptable damage linked to structural integrity*. Some damage, including deformations and cracks, is accepted. In general, damage to occur should comply with the following conditions:

   (a) The damage should be repairable using traditional or historical techniques for repair or maintenance (substitution of a limited number of stones, refilling of joints…)

   (b) Additional or irreversible damage should be acceptable to very limited extent.

   (c) The cost of loss in immovable cultural value caused by the damage due to the earthquake must be smaller that the corresponding cost caused by a more heavy and invasive strengthening designed to prevent this damage.

(2) *Acceptable damage linked to public safety and movable contents*. The need to avoid injuries or casualties in buildings, which normally host large amounts of users or visitors, and avoid losses of significant movable heritage, which normally is present in architecture heritage buildings, should lead to seismic upgrading preventing any kind of damage which can compromise the safety of people. Even in these cases, certain damage might be acceptable (some cracks deformation) provided it does not cause significant risk to people. For instance, limited cracking and deformation may be acceptable provided that they do not compromise the stability of the building.

(3) *Acceptable damage linked to the integrity of fixed artistic heritage*. As mentioned in Section 4.2.6, the case of buildings containing a very valuable and fixed artistic decoration requires another approach. In these cases, the possibility of accepting certain damage is limited by the

possible deterioration that even small cracks and deformations may cause to the artistic contents.

4.5.2.3 Selection of solutions

The selection of a possible strengthening strategy should be derived from the consideration of the aspects mentioned in Section 4.2.4 (seismicity, structural design, state of conservation and use) together with the level of acceptable damage. These conditions contribute to either the hazard (seismicity) or the vulnerability of the building (structural design and state of preservation) and altogether, they determine the level of risk experienced by the building and its values (see Section 2.3).

Two different conditions, to be simultaneously complied with, are proposed in order to select an adequate strengthening strategy.

The first proposed condition addresses the requirement for a seismic upgrading preventing from unacceptable losses or damage according to Section 4.5.2.2. In short, the losses caused by the design earthquake should be limited to the acceptable damage:

Condition 1:

Losses due to earthquake in strengthened building ≤ Acceptable damage

The terms in the above condition should include the damage or losses caused in the both the structure and the fixed artistic heritage (frescoes, decoration) existing in the building. That way, the equation is worth also for the case in which the main aim of the seismic upgrading is at preserving the integrity of existing fixed artistic heritage.

Condition 1 is intended to provide a minimum requirement of seismic upgrading.

Figure 4 illustrates the application of *condition 1*. A possible relation between the potential cultural loss and the risk is compared with the corresponding curve for the structure upgraded according to different strengthening solutions S_1, S_2, S_3. All the solutions cause a cost for even null risk C_{01}, C_{02}, C_{03} due to the alteration of the structure meant by their implementation. In turn, all the solutions are meant to improve the response of the structure (and thus to reduce the potential losses) to a certain extent. According to condition 1, a certain solution S_i, causing a certain upgrading effect, should be only used for seismic hazard levels above the value H_{in} where the corresponding curve intersects that of the unstrengthened structure. For any solution, a sort of minimum seismic hazard can be determined below which the solution should not be used.

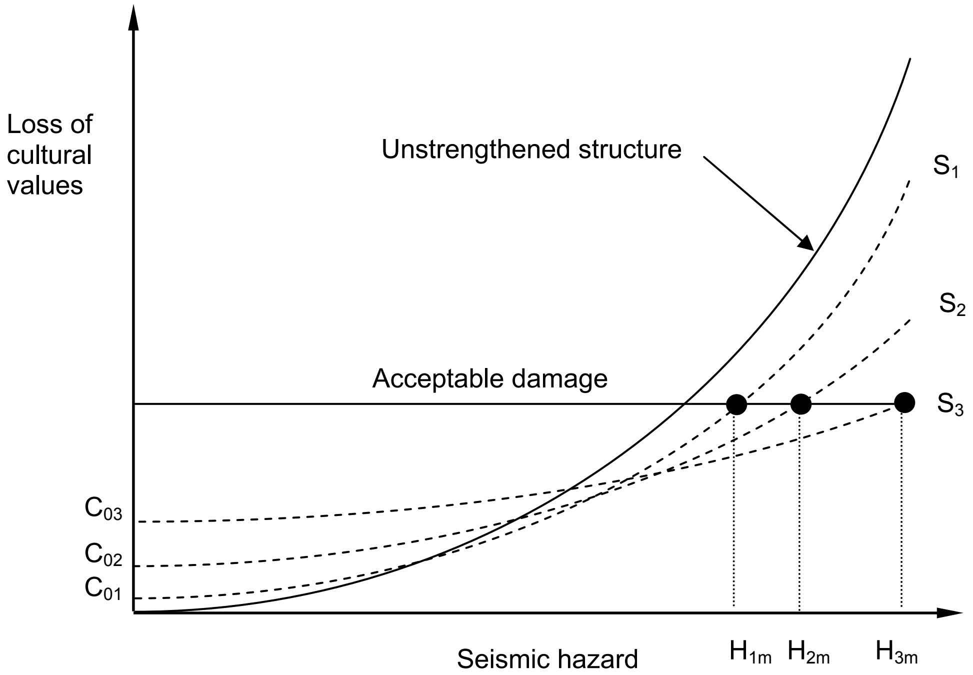

Figure 4: Possible relationship between hazard and cultural loss for different seismic upgrading solutions S_1, S_2, S_3. Upper hazard levels associated to the different solutions.

A second condition is introduced with the purpose of limiting the losses caused by the implementation itself of a seismic strengthening. It is proposed to limit the possible cost in cultural values caused by the strengthening operation itself (see Section 4.2.6) to the possible costs or losses that could be caused by the earthquake on the structure in its un-strengthened condition:

Condition 2:

Cost of implementation ≤ Losses due to earthquake in unstrengthened building

In other words, the cost of the implementation of the strengthening should never be larger than the potential losses caused by the earthquake.

Figure 5 illustrates the application of *condition 2*. An acceptable damage level (based on the considerations of Section 4.5.2.2) is set up in order to determine the best strengthening strategy. The level of acceptable damage does not depend on the seismic hazard since it is in essence derived from the characteristics of the structure and its possible artistic contents. The intersection of the horizontal line describing the acceptable damage with the curves corresponding to a possible solution S_i will provide a limit H_{im} for the maximum seismic hazard for which this solution is worth.

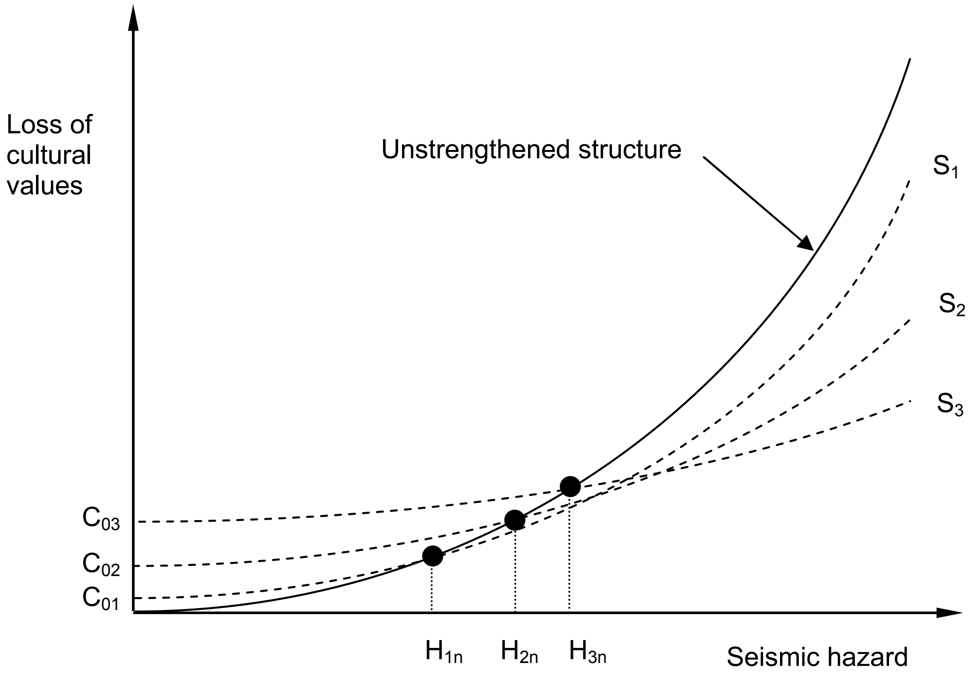

Figure 5: Possible relationship between hazard and cultural loss for different seismic upgrading solutions. Lower hazard levels associated to different solutions.

The combination of conditions 1 and 2 will lead to determine an interval of acceptance, in terms of seismic hazard (H), for any possible solution,

$$H_{in} \leq H \leq H_{im}$$

Among the acceptable solutions for a seismic hazard H (the ones complying with the above equation), the one showing the more strict H_{im} limit should be preferred because it will normally cause the lesser C_{0i} cost. A solution for which the limit H_{im} equals the seismic hazard H would be an optimal one causing the lesser necessary cost C_{0i}.

This criterion is intended to work also for historical buildings with severely limited acceptable damage due to the existence of fixed artistic heritage. In these cases, the artistic heritage is to be preserved intact (or almost), which requires a very low structural damage on the strengthened structure in case of earthquake. Conversely, it will be acceptable to cause a certain loss of cultural value on the structure by implementing significant (and structurally altering) strengthening.

For a construction of this kind, the diagram relating cultural loss and seismic hazard will look like the one in Figure 6, with the more restrictive curve to limit the acceptable damage and a comparatively larger initial loss caused by the implementation of the strengthening.

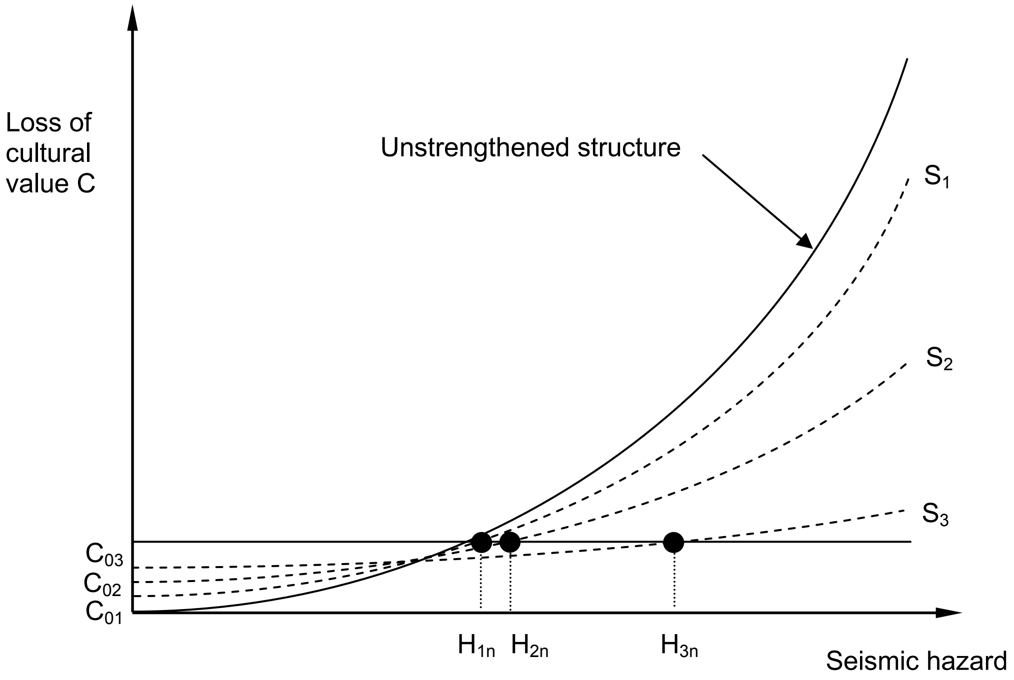

Figure 6: Possible relationship between hazard and cultural loss for different seismic upgrading solutions in the case of a structure with valuable fixed artistic heritage.

4.5.2.4 Decisions related to public safety and movable heritage

In some cases, a respectful and reasonable upgrading might only provide a limited and perhaps insufficient seismic improvement. As a result, the upgraded structure might not be safe enough as to host large amounts of visitors or to store valuable movable cultural heritage due to the risk of partial failure during an earthquake. Rather than implementing a more heavy and invasive strengthening, the designer (in agreement with the authorities) should consider the possibility of limiting the use of the building (in particular, the number of visitors and frequency of visits, and replacing the movable heritage by clearly identified replicas or placing it in a safer location) as a way to reduce the risk for people and heritage.

In the case of valuable monuments, the use should be considered on the base of acceptable upgrading. Whenever a foreseen use requires heavy upgrading and significant transformation of the structure, the use should be reconsidered so that it is compatible with limited and respectful upgrading.

5 FINAL REMARKS

Historical structures encompass a valuable cultural heritage that our modern societies are prone to preserve for many social, cultural and economical reasons. The conservation of the rich heritage structures requires, among other aspects, to consider their possible seismic upgrading and thus to reduce the likelihood of damage or destruction caused by earthquake, especially in high seismicity areas. Seismic upgrading in historical structures is thus not only oriented to public safety, but also to preserve the cultural values embedded in the structure – a valuable testimony of construction history and a cultural value in itself – and its possible artistic contents (immovable and movable).

Conventional codes and methods, mostly oriented to modern structures, may not be adequate for the study of ancient structures and may lead to inaccurate or misleading results. Instead, a more comprehensive and flexible approach is to be used taking into account possible evidence coming from history, the inspection of the structure in its present condition, monitoring and structural analysis. The evidence obtained through this approach may contribute to a more sound understanding of the real condition of the building and real needs for seismic upgrading.

Seismic upgrading of historical structures is a complex tasks because any action oriented to improve the seismic response of the structure – and thus to avoid or reduce losses due to the earthquake – will cause an alteration to the structure, to its materials and original strength mechanisms, and thus also some initial – if difficult to quantify – cultural losses. Any solution intended to improve the seismic response of the structure must be carefully analyzed for an adequate balance between the benefit (the gain in seismic strength) and the cost (the possible losses caused by its implementation).

BIBLIOGRAPHY

CEN. 2005. EN 1998-3. Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings. Brussels : European Committee for Standardization.

Charter for the Restoration of Historic Monuments (the Athens Charter). 1931. First International Congress of Architects and Technicians of Historic Monuments, Athens.

Esponda, M. 2003. *Evolution of the criteria of intervention with reinforced concrete in the restoration of buildings in Mexico and Spain* (in Spanish). Barcelona: Universitat Politècnica de Catalunya.

FEMA. 2001. FEMA-356 Prestandard and commentary for the seismic rehabilitation of buildings. Washington, D.C. : Federal Emergency Management Agency.

International Charter for the Conservation and Restoration of Monuments and Sites (the Venice Charter). 1964. Second International Congress of Architects and Technicians of Historic Monuments.

ISCARSAH 2001. Recommendations for the Analysis and Restoration of Historical Structures. ISCARSAH- International Committee on Analysis and Restoration of Structures of Architectural Heritage, ICOMOS.

Ministerial Decree (D.M 24/01/1986): technical regulation concerning aseismic constructions (in italian). Rome: Ministry of Public Works.

Ministerial Decree (D.M 16/01/1996): technical regulation for constructions in seismic areas (in italian). Rome: Ministry of Public Works.

O.P.C.M. 3431. 2005. Technical rules for the design, the assessment and the seismic upgrade of buildings (in Italian). Rome: Ministry Council.

TC 98/SC 2 (2001) Bases for design of structures – Assessment of existing structures. ISO 13822:2001. Geneva: International Organization for Standardization .

Chidiac, S. E., Foo, S. 2002. Guidelines for the seismic assessment of stone-masonry structures. Technology Directorate Architectural & Engineering Services. Public Works & Government Services Canada. Hull, Quebec

Chidiac, S. E., Foo, S. 2002. Guidelines for the seismic upgrading of stone-masonry structures. Technology Directorate Architectural & Engineering Services. Public Works & Government Services Canada. Hull, Quebec