ABSTRACT: The Recommendations of ICOMOS / ISCARSAH provide a set of principles and guidelines for the analysis and restoration of historical structures laid out in the Venice Charter. According to the Recommendations, conservation must be based on the thorough knowledge of the history, structural problems and needs for intervention. The Recommendations recognize three different phases in the study of historical constructions, namely diagnosis, safety evaluation and design of intervention. In each of these three phases, they provide concepts and methodological guidelines intended to assists the analyst in obtaining scientifically derived conclusions on the true condition of the building, its structural safety and the needs of repair or strengthening. In the present paper, the Recommendations are introduced and discussed with a focus on the difficulties that the analysts and designers may face in their attempts of applying them in practice. Complementary reflections, addressing the three aforementioned phases of the study, are also presented.

1 INTRODUCTION

The restoration of architectural heritage has historically encompassed very different attitudes towards the structures of monuments. With Viollet-le-Duc and other 19th C. researchers, monuments began to be appreciated as a testimony of past achievements in the conception and construction of structures. However, the structure was not yet regarded as a feature deserving the same care and respect dedicated to artistic components. The structure was still seen as a utilitarian contrivance meant to resist; any actions carried out on the structure, no matter the alterations caused, were considered acceptable provided they actually ensured strength and did not compromise the external aspect or the artistic content of the building.

During the first half of the 20th C., structural restorations often conveyed significant changes of the materials and the structural arrangement of the building (Fig. 1); obtrusive devices made of modern materials such as reinforced concrete or steel were often implemented in order to transform the structure of the building and cause it to behave more like a modern construction. Knowledge of early materials and calculation methods did not provide an adequate understanding of the current resistant capacities of ancient structures; available inspection procedures were not able to supply an accurate understanding of the real condition of the building. Above all, carrying out a significant alteration of the original structure, with the subsequent reduction of authenticity, was not regarded as a loss of cultural values. This stage is well represented by the Athens Charter (1931), according to which the experts [...] approved the judicious use of all the resources at the disposal of modern technique and more especially of reinforced concrete. They specified that this work of consolidation should whenever possible be concealed in order that the aspect and character of the restored monument may be preserved.

It is only in recent times, after the adoption of the Venice Charter (1966) that the structure of monuments has become to be considered as an intrinsic and valuable part of the architectural
heritage. 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; they testify to certain stage of construction history 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. As for the cultural heritage, proper restoration works must focus on preserving the original condition of structures and, if repair or restoration works are needed, they must cause minimum changes. When referring to the original condition of the structure, this not only means geometry and materials: the authenticity of the mechanical and resisting principles governing the structural response (the essence or nature of the structure) are also to be preserved and further repair or strengthening works should respect these.

Modern techniques for non-destructive inspection and computational modelling may contribute very significantly to acquiring a profound understanding of the nature of the structure (materials, morphology, and resisting mechanisms) and the actual origin of its structural problems. A profound understanding is paramount to achieve respectful and minimum interventions. However, structural restoration must also face safety requirements and thus it is necessary to ascertain strength for both normal and extraordinary actions. In some cases, authenticity (respect for the original configuration and nature) and safety (enough capacity to resist possible actions) may seem in conflict. 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 engineer or the architect committed to structural restoration.

The complexity and difficulties involved in structural restoration have recently led the International Scientific Committee for the Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) of ICOMOS to prepare a set of Recommendations for the Analysis and Restoration of Historical Structures under the leadership of Prof. Giorgio Croci (ISCARSAH, 2001). These principles have been officially adopted by ICOMOS in 2003. The following paragraphs include a discussion on the main ideas developed by the ISCARSAH Recommendations. Emphasis is made on the possible difficulties which may be encountered by analysts and designers in the attempt of applying the restoration principles in practice, and the way the Recommendations can be used to face these difficulties. Additional reflections are included on different issues (in particular, on the evaluation of safety and the design of minimum interventions).

Figure 1: Use of reinforced concrete (left) or steel frames (right) to modify the structure of historical constructions.
Figure 2: Different restoration approaches. Left: the material is continuously replaced according to traditional maintenance practices. Right: Repair is preferred; the original material is only replaced when required by safety or durability considerations.

2 PRINCIPLES AND METHODOLOGY OF STRUCTURAL RESTORATION

The following paragraphs offer a synopsis of the main ideas implicit in the principles and the guidelines of the Recommendations. For a first-hand and more detailed vision, the reader is encouraged to read and become familiar with the original source (ISCARSAH, 2001).

The study of ancient buildings and the design of any interventions must be carried out following procedures adequately supported by scientific insight and methodology. The scientific reasoning must include both theoretical concepts and experimental evidence. Previous experience resulting from scientifically acquired knowledge must be considered and integrated in the process leading to the diagnosis and the design of the interventions.

However, the understanding of the building and the design of possible interventions can not be only determined from pure scientific insight. Historical constructions are not abstract beings and can only be understood within their historical and cultural contexts. The understanding of the architectural values and the legitimacy of the possible repair or strengthening strategies are, to a certain extent, dependent on the cultural background of the building. In Europe, for instance, conservation is mostly linked to the preservation of the original material composing the historical structure. In Asia, and particularly in China and Japan, the maintenance of ancient timber constructions has been historically carried out by replacing decayed material and damaged structural members with new ones; ancient and traditional crafts and construction techniques have been preserved and are still used to maintain and replace material following historical practice. Thus the study of the architectural heritage must result from a combination of both scientific and cultural knowledge and experience (Fig. 2).

Structural engineering supplies the technical and scientific support necessary to safeguard the cultural and historical value of the building. However, structural engineering cannot be implemented in a conventional way, or cannot be applied merely as in modern structures. Historical structures are complex entities often made with diverse materials and forming sophisticated geometries. These structures may experience a variety of actions, occurring over long periods of time or associated to long-term processes. They may endure long-term deteriorating effects (such as material decay) and even experience severe damage or collapses due to accumulated damage. They are subjected to transformations and repairs (either beneficial or damaging) throughout their lives. Because of this complexity, the study of historical structures requires a more general and flexible application of structural engineering techniques by taking into consideration the impact of history. Historical investigation constitutes an indispensable source of understanding and must be integrated, even if only in a qualitative way, in the analysis.
Quantitative analysis may not be enough to actually understand and form conclusions on the condition of a historical building. However, quantitative analysis is needed by all means in order to define the structural deficiencies and to design an adequate intervention. Any planning for structural conservation requires both qualitative and quantitative information. Qualitative data emerge from historical research and inspection (direct observation of material decay and structural damage). Quantitative data may result from specific tests, monitoring and structural analysis using appropriate mathematical models. This combination of approaches makes it very difficult to establish general rules.

Codes and rules oriented to the design of modern structures may not be adequate when applied to 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). With only the concurrence 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 are obviously overcome by accepting the aforementioned more general approach.

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 (Fig. 3). 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 with regard to the safety level required. This is, by far, a more conflictive and sensitive aspect that the one referred to above. Assuming that the calculation methods and conclusions are reliable enough, one may be forced to choose between accepting major (and economically costly) alterations for strengthening and accepting a reduced safety level – and a larger risk for human beings. The latter may seem not acceptable at a first glance, the need to provide adequately safe conditions to possible users or visitors being non-negotiable. However, 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 (such as many churches in Portugal or Italy). Seismic “improvement” of existing buildings provides a possible way of confronting this difficult dilemma (see in section 5.4).

Conventional tools for structural evaluation often lead to the division of the structure into a set of substructures or structural components which are assessed independently. Conventional methods are normally oriented to the understanding of the performance of individual elements rather than of the behaviour of the structure as a whole. However, historical structures frequently require a holistic approach considering the building as a whole. This is so because of the organic character of many historical structures, where the entire geometry and all the structural components are arranged to satisfy overall equilibrium. Masonry composed of arches and vaults sustained on piers and buttresses (arch or vaulted systems) encounter equilibrium thanks to the geometrical organization of the whole, each structural member, with its appropriate geometric shape, being indispensable for adequate overall stability.

The scientific approach calls for the participation of different experts covering a range of skills (engineers, architects, historians, archaeologists, mineralogists, geophysicists…). The need for knowledge and experience involved in the understanding of historical buildings is paramount and cannot be covered by a single professional, a variety of different contributions being required. In turn, this aspect calls for the capacity to work within a multi-disciplinary group and to communicate with different specialists. Working successfully in a multidisciplinary group requires shared objectives, converging methodological practices and a common vocabulary.
Similarly, the need for sound scientific methodology and knowledge requires the activation of a multi-faceted approach involving different activities. The main activities to be integrated in the study of a historical structure (or the elements of its analysis) are historical investigation, inspection, monitoring and structural analysis. Some of these (historical investigation and inspection) are qualitative; the others are quantitative (monitoring and structural analysis). The confluence of these activities permits a consistent application of the scientific method. On the 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). This model also includes certain hypotheses on the material properties, internal morphology and structural arrangement. These second group of hypotheses are needed because, no matter what the effort carried out in the inspection and experimental description, it will never be possible to have a fully realistic and comprehensive description of the construction. 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 it are in turn validated or corrected. Once calibrated, the model can be used to make predictions on the response of the building under different actions.

In particular, historical research and structural analysis should be adequately connected. Historical research can provide data or discover facts meaningful for the understanding of past and present structural behaviour. In turn, structural analysis may help answer to historical questions. In the case of the Cathedral of Tarazona, for instance, the knowledge on the different architectural alterations experienced by the building through its history allowed the modelling of their structural effects in an accurate way and thus establishing satisfactory correlations between existing damage and analytical predictions (Roca, 2001). In the study of Mallorca Cathedral, the simulation of the construction process, known thanks to careful historical research, was essential to actually understand the causes and significance of the existing damage and deformation (Roca, 2004).

The study of a historical construction consists of three subsequent phases, namely diagnosis, safety evaluation and design of the intervention. 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. If these stages are performed incorrectly, the resulting decisions might be inadequate for the building. Poor judgement may result in either conservative and therefore heavy-handed conservation measures, or insufficient ones causing inadequate safety levels. The three 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 (for instance, monitoring or structural analysis can be utilized during the diagnosis and also to assess the response of the strengthened structure).

Despite all the effort invested in applying this general approach in a consistent way, there will always be room for subjectivity and uncertainty. There exists an opportunity for subjectivity in the study and safety assessment of an historic building according to the process described above. There will always be uncertainties in the data assumed. The difficulties of a precise evaluation of the phenomena may lead to conclusions of uncertain reliability. The room for subjectivity and uncertainty must be recognized and even objectively stated together with their possible incidence in the reliability of the conclusions presented. According to the Recommendations, the care taken in the development of the study and the reliability of the results should be presented and discussed in an *Explanatory Report*. This report requires a careful and critical analysis of the safety of the structure in order to justify any intervention measures. The report should explain the uncertainties, the reliability of the data and the hypotheses considered.

In conclusion, the difficulties encountered in the study of ancient structures (in particular, the limitation of codes and conventional methods for modern structures) are overcome by adopting the aforementioned more general approach encompassing and reconciling quantitative and qualitative evidence. At least four possible sources of knowledge (history, inspection, monitoring and structural analysis) can be considered and combined as part of a scientific approach, to draw conclusions on the condition of preservation, causes of damage or decay and need for intervention. In any case, there is always room for uncertainty and subjectivity, and this fact must be clearly acknowledged.

The way all these aspects influence on the process leading to diagnosis, safety evaluation and design is discussed in the following sections.

### 3 DIAGNOSIS

The final purpose of diagnosis obviously lays in the characterization of the real condition of the structure and the real causes of the problems experienced by it (deformations, structural damage, material decay…). Diagnosis requires, whenever possible, the combination of a set of different activities, including historical research, superficial and deep inspection, monitoring and structural analysis.

Historical research provides information which is essential for an accurate diagnosis. This research should supply information on all the facts or events having had a sensible impact on the building, including the techniques and skills used in its construction, the subsequent changes in both the structure and its environment, historical actions (earthquakes) or any events that may have caused damage, failures, reconstructions, additions, changes, restoration work, structural modifications, and changes of use. This information is obviously needed to draw reliable conclusions on the true origin of damage or alterations observed in the building.

Inspection is needed to identify existing decay and damage, determining whether or not the phenomena have stabilised, deciding whether or not there are immediate risks and if urgent measures have to be undertaken, or identifying any ongoing environmental effects. Inspection includes field research and laboratory experiments, the latter aimed at identifying the mechanical, physical and chemical characteristics of the materials, the stresses and deformations and presence of any discontinuities within the structure. Internal morphology requires either non-destructive or minor destructive tests. Non-destructive tests should obviously be preferred, but if additional tests are necessary, a cost-benefit analysis (by comparing benefit in information and the possibility of a reduced structural intervention against the loss of culturally significant material). It is always adequate to use different methods to obtain redundant information; minor destructive test provide direct information which can be used to calibrate the non-destructive, but indirect, methods.

Monitoring enables the acquisition of quantitative information at different stages of the study or intervention of a building. This includes previous, long term characterisation of the response of the building, survey of auxiliary remedial actions, survey of final strengthening actions dur-
ing their implementation or long-term survey of a strengthened construction. Dynamic monitoring can be used not only to characterize the dynamic response of a building but also to identify more general morphological or structural features.

Structural analysis is needed to model the response of the structure under different actions and to quantify its strength. This structural analysis involves the adoption of a certain model (be it analogical, analytical, numerical…). Models are needed to reduce reality to a limited number of concepts and variables. Constructing a model calls for the acceptance of a set of hypotheses. These hypotheses are to be calibrated by comparing the predictions of the model with empirical evidence resulting from the rest of the activities (history, experiments, monitoring). Agreement between the predictions and the observed reality may require modified or improved hypotheses. Structural analysis, in this way, provides three different complementary opportunities: (1) Through the validation of the hypotheses supporting the model, a deeper insight is gained on the structure (materials, morphology, structural principles…); in this way, using and calibrating the model provides additional information or certainty. (2) Through the simulation of possible phenomena having acted on the structure (weights, settlements, structural modifications…) it is possible to gain insight on the causes of existing damage. (3) Once validated, the model can be used to draw additional predictions on the response of the structure under different actions (new live loads, earthquakes etc.) and assess its capacity to actually resist them. In any case, it must be recognized that no model represents the full reality and that the possibilities of models are always limited. Models utilized in practice are a compromise between realism and simplicity. However, models must include all the aspects judged to be relevant for the description of the real behaviour of the structure, including major alterations and damage. (An extended discussion of the activities involved in the diagnosis can be found in Kelley and Look (2005) and Roca (2004).

4 SAFETY EVALUATION

4.1 The problem

As stated by the Recommendations, the safety evaluation, which follows from the diagnosis, is where the decision for possible intervention is determined, and needs to reconcile qualitative and quantitative analysis. The assessment of safety is seriously affected by two types of problems.

Firstly, as already mentioned, there may be major uncertainty attached to the data obtained from inspection and survey. This uncertainty may affect the description of the geometry, internal morphology, properties of the materials and the distribution and extent of damage and deformations. There is also significant uncertainty regarding either permanent or extraordinary actions. Earthquake, in particular, and other extraordinary actions associated to long-term periods are inherently uncertain and cannot be described in an absolute way (in terms of magnitude, frequency, or direction of incidence).

Secondly, safety evaluation requires a realistic model (whatever its nature: analytical, numerical, analogical…) able to represent the strength of the structure and to provide a measurement of the structural response to different actions or combinations of actions. In recent years, numerical methods for the analysis of masonry and wooden structures have experienced a very significant development. Particularly, a variety of reliable approaches exist today to accurately model the ultimate responses of masonry structures (Lourenço, 2002).

Classical approaches may also be used successfully for the assessment of safety. Hooke’s principle on the analogy between the shape of deformed strings and that of arches in equilibrium is still useful and inspiring. Plastic analysis, based on the limit theorems of plasticity, constitutes a very realistic and affordable technique for the analysis of masonry structures composed of arches and vaults. Some of the more recent and interesting numerical developments are based on limit analysis. In a way, they constitute a conjunction of classical approaches and modern numerical methods.

Given the significant progress experienced in mathematical modelling of masonry structures, together with the permanent validity of classical tools, it can be said that the difficulty of safety assessment is not found in the availability of adequate tools. The difficulty lies still in the need for reliable input data and adequate methods for the calibration of the model.
The aforementioned limited applicability of available rules and codes (mostly oriented to modern structures) causes a very delicate and difficult position to users. As stated, codes prepared for the design of modern structures can lead to inadequate conclusions when inappropriately applied to historic structures. The enforcement of codes (particularly seismic and geotechnical codes) can lead to drastic measures conveying loss of historic fabric or alteration of the original structure. Conversely, ignoring legal codes may generate a situation of legal uncertainty to engineers or architects involved. This conflict can only be overcome with the active implication of the authorities, their understanding of the problem and their acknowledgement of the capacity of judgement of the engineer or architect. Schmidt (2002) has elaborated a useful document on this issue. The document, addressed to customers and authorities, expresses the need for a sound acceptance of the role of the engineer and his legitimacy for taking decisions, beyond the specifications of rules and codes, with the recognition and support of authorities.

Another way to overcome the conflict can be found in the approval of codes or regulations specifically oriented to existing structures. The concept of seismic “improvement” of existing buildings, as defined by the Italian seismic code (P. C. M. 3431, 2005), constitutes an example. The recognition of the possibility of “improvement” offers a legal frame for the 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.

ISO 13822 (TC 98/SC 2, 2001) also provides useful statements, such as the recognition of the qualitative approach and the value of past-performance. However, ISO 13822 lacks specific considerations for structures of architectural heritage.

As part of the entire study of an historical construction, safety evaluation requires also a broad approach not only involving the application of codes or structural calculations. The approach may also exploit qualitative evidence in combination with the quantitative one; historical and experimental understanding may be combined with quantitative evaluation. As stated by the Recommendations, the architect or engineer charged with the safety evaluation of an historic building should not be legally obliged to base his decisions solely on the results of calculations.

It must be stated that the main objective of the broad approach is not to reduce the safety or the reliability of the assessment. The emphasis must be placed in carrying out an even more objective and reliable assessment by using all the available sources of evidence within the frame of a scientific methodology. The emphasis is in avoiding, in any case, risk to human life. The principle of minimum intervention, however, is also to be considered and reconciled with the safety requirements. A realistic understanding of the condition of the building may lead to a more accurate identification of the repair or strengthening operations and thus to the adequate choice of the minimum intervention compatible with the safety requirements.

4.2 The method

As for the diagnosis, the broader approach consists of applying different investigations, each providing its own contribution. Their combination will produce the best possible result (the best possible conclusions) based on the data available. The approaches to be considered are, in essence, those already mentioned in section 3. Their counterparts, when performing the safety assessment, are historical knowledge, qualitative approach, experimental approach and analytical approach.

The historical approach. Once again, history can be seen as an experiment carried out at true geometric and time scales. Investigation of historical records can reveal important facts concerning the strength and performance of the building. Insight on past performance can provide hints on the capacity of the structure to resists gravity loads or extraordinary events such as earthquakes.

However, the historical approach, as any individual approach, is not enough to make reliable conclusions. The capacity of a building to resist its gravity loading can be compromised by damage developing in the long term or by the decay of the material (Fig. 4). New earthquakes can severely damage a structure, or even cause the collapse, in spite of it having successfully resisted other earthquakes in the past. Accumulated damage can, again, weaken the seismic resistance of a building. It can be said that the structure changes after each earthquake and this limits the possibility of comparing past and present. Moreover, earthquakes may differ very much in orientation, duration and seismic frequency; each seismic event constitutes a genuinely distinct
action. The case of important monuments (such as The Civic Tower of Pavia and or the Cathedral of Noto, Binda et al., 2003, and The Basilica of Assisi, Croci, 1998) which collapsed or were severely damaged in recent times, after long and satisfactory past performance, clearly illustrates these statements. The insights gained through historical investigation must be set against the evidence provided by the other approaches.

Figure 4: Effects of long-term deterioration in ancient arches.

The qualitative approach. Another approach (the qualitative one) results from analysing the strength response of a number of buildings similar to the one being studied. The behaviour of other buildings is assessed empirically (i.e. their response in the event of likely actions, such as earthquakes, is noted) and the corresponding conclusions are extrapolated in the case of other buildings. The possibility of extrapolating (and the extent of it) must be judged by the analyst. In any case, sufficient similarity must exist in terms of dimensions, structural organization, morphology and materials.

This way of reasoning has produced very interesting approaches during the last years as a consequence of the systematic study of the performance and collapsing mechanisms of buildings affected by earthquakes (Lagomarsino et al., 2004). Simple but very useful assessment methods, based on the study of typical collapsing mechanisms, have been created after a careful study of the effects of earthquakes in a large number of buildings. Comparison and extrapolation, supported on wide collective experience, has become a common way of assessing the condition and weaknesses of churches or vernacular buildings built with similar construction techniques. In turn, the comparative study of the earthquake performance of certain worldwide recurrent building types (such as timber infill-frame construction, see Lagenbach, 2006), has provided insight on their actual virtues and to draw conclusions on their possibly earthquake-resistant nature.

The experimental approach. A direct assessment of the strength capacity of structures can be obtained by on-site experiments involving the application of real loads. Note that the aim of these experiments is not the identification of mechanical properties (as in the case of diagnosis, see section 3) but the direct appreciation of the capacity of the structure to resist a real action. Direct experiments involving significant loads can hardly be carried out on the entire structure; more likely, the experimental approach will be utilized to assess the capacity of individual members such as floor-slabs, vaults or stairs, to resist a certain vertical loading. Due to their risky and difficult execution, direct load tests have a very limited application.

Another possibility is offered by laboratory experiments. The laboratory offers a limited risk and controllable conditions. Laboratory tests can be carried out on specimens or structural components taken from the real structure or on purpose built laboratory components or models acting as mock-ups of their real counterparts. The applicability of the first strategy is limited because of its destructiveness; moreover, taking unaltered specimens from the real structure to the laboratory may be difficult. The second one may result too indirect because of the limited realism of experimental models; the main difficulty will be normally found in reproducing the real materials and especially lime mortar, whose long-term hardening process can not be simulated.
in a short-term test. Scaled models may be preferred in some cases because of economical reasons or merely because of space limitations.

*The analytical approach.* Compared to the qualitative approach, an inductive procedure, the analytical approach constitutes a deductive process. The information on the structure, morphology and actions is invested in constructing a structural model. The model is then used to deduce (predict) the response of the building. The model may provide a quantitative measure of safety – a safety factor - obtained as the quotient between the magnitude of the response (the strength) and that of the action applied. Obviously, the actual predictive capacity of a model depends on the reliability and completeness of the data provided; lack of reliability, uncertainties and incompleteness will severely compromise the validity of the estimated safety level. Since data are always limited and liable to uncertainty, an absolute, totally objective measurement of safety is not possible. The analytical approach is not enough by itself and must be also undertaken in combination with the other approaches; numerical estimations are also to be confronted and reconciled with the evidence yielded by the other investigations.

5 DESIGN OF INTERVENTION

5.1 The problem

Following the Venice Charter (1966), the Recommendations state that the intervention should respect the original concept, materials, construction techniques and historical value of the structure to the greatest possible extent. The removal or alteration of any historic material or distinctive architectural features should be avoided whenever possible. The Recommendations also acknowledge that conservation and strengthening must consider not only the results of an objective safety evaluation, but also the historical and cultural significance of the structure.

The building should be understood as a complex amalgam resulting from a historical process, in which not only the original elements, but the subsequent modifications and alterations are recognized as a valuable part of it and must also be respected. As the Recommendations state, when imperfections and alterations have become part of the history of the structure, they should be maintained provided they do not compromise the safety requirements. The distinguishing qualities of the structure deriving from its original form or any significant historical changes should not be destroyed due to any necessary actions.

Thus, the wish for respect involves not only the architectural (formal) values, but also the structural features and resisting mechanisms developed by the structure. Working structures are expected to suffer mechanical effects, such as cracks and deformation, both in the short and long term. This is an inherent consequence of the mechanical work and should not be considered as an anomaly requiring a certain therapy. Damage and deformation can have a more anomalous origin –such as major soil settlement, inadequate structural response, accidents, extraordinary actions or artificial intervention - but they should be also regarded as part of the history of the structure (Fig. 5). Maintenance care carried out according to traditional or historical practices can be considered for intervening in these types of alterations (for instance, cracks due to soil settlements can be re-pointed with lime mortar following traditional practices). In some cases, however, normal maintenance practices may not be enough to provide the safety or durability required and a more important intervention may be necessary. In some structures, especially in structures showing significant deterioration or weakness, the wish to provide an adequate safety level, by means of a certain strengthening, may seem in contradiction with the respect towards original materials and historical value. In some cases, the strengthening envisaged may require a significant alteration of original parts or modification of the original resisting mechanisms. This should not be regarded as in contradiction with the statements of the Recommendations.

Strengthening requirements and respect to original values can be accommodated by displaying an adequate engineering approach to the problem. The following considerations, related to (1) methodology, (2) design requirements and (3) selection of optimal solutions, are proposed as a way to conciliate intervention and respect towards authenticity.
Methodology

The design of the intervention is the third phase of the entire process involving the study of an historical structure coming after the diagnosis and the safety assessment. The design process should not be regarded as an independent activity, but as a phase fully integrated with the entire process. The principles of scientific and methodological consistency and the need for a broad approach involving different and multidisciplinary activities should also be taken into consideration and effectively applied in designing the intervention.

The design of the intervention must be scientifically linked with the prior diagnosis and safety assessment. The intervention must accurately act on the precise causes of the problems (determined from the diagnosis) and must adequately address the needs for repair or strengthening resulting from the safety assessment. The purpose and outcome of the intervention must be rationally connected with the conclusions of the diagnosis and safety assessment. As a consequence, only indispensable actions are to be undertaken. No actions should be undertaken without demonstrating that they are indispensable to meet the repair or strengthening needs highlighted by the diagnosis and the safety assessment. Moreover, all interventions must be in proportion to these needs.

The need for a broad understanding encompassing different approaches is also applicable to the design of the intervention. Numerical modelling and experimental analysis—among other possible activities—should actually be considered and utilized for the design and the assessment of the intervention.

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 any 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 nil intervention. Structural analysis can be utilized to numerically simulate the effect of the intervention and obtain a prediction on the response of the strengthened structure. In this way, monitoring and structural analysis (and their combined use) may help reduce the extent of the intervention.

The qualitative approach described in section 4 can also be used here to identify traditional strengthening devices or structural arrangements which, as proven by their past performance in the case of earthquakes or other extraordinary events, actually succeed in improving the response of the structures. Construction history and tradition provide a variety of repair or strengthening solutions (Fig. 6). The validity of these solutions to a particular case can be assessed on the basis of their past performance in similar cases.
Monitoring is also useful to control the execution during the strengthening of a structure. Because of this, measures that are impossible to monitor during execution should not be allowed. Any proposal for intervention should be accompanied by a programme of monitoring and control to be carried out, as far as possible, while the work is in progress.

Computer simulation can be useful to assess the sequential process leading to the implementation of real strengthening in a construction and thus distinguish the most delicate operations involved or the need for auxiliary safety measures.

5.3 Design criteria

A set of criteria is taken into account in order to design operations with limited and acceptable impact on the original structure. These requirements have already received broad dissemination through the charters and regulations dealing with structural restoration; they are currently familiar to engineers and architects who take them in consideration in designing possible interventions. They include the well-known criteria of minimum intervention, compatibility, durability, non-obtrusiveness, reversibility and controllability.

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.

The materials and the technical devices used to repair or strengthen a structure must be compatible with the existing 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 through 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 to 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 the application of additional gravity loads (mechanical compatibility).

For similar reasons, 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.

Non-obtrusive (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.

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.

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.
5.4 Selection of optimal solutions

These conditions should not be understood as absolute requirements, but as convenient features normally leading to satisfactory solutions. The fact that complying with all these criteria may be impossible in some cases should not be taken as a reason to ignore them. The attempt to satisfy the conditions to the greatest possible extent – by using these conditions as guidelines or even inspirational principles - will contribute in creating and designing adequate interventions consistent with restoration principles.

In no case the above criteria should be enforced absolutely. Their application may encounter significant or even insurmountable difficulties in practice. Moreover, their full and simultaneous enforcement may face, in some cases, significant contradiction or conflict. In particular, minimum intervention and safety may appear in conflict in the case of buildings showing significant structural deficiencies or a severely damaged condition.

It must be recognized that perfect solutions (that is to say, solutions fully complying with all the stated criteria) may not be possible. Hence, the role of the engineer or architect consists of selecting an adequate solution which complies with the criteria to an optimum extent. Choosing the best solution is a responsibility of the designer and requires adequate expertise and personal judgement. Therefore some advice is offered (perhaps as mere ideas) which can assist the designer in exercising his judgement.

The first and essential aspect comes from the need for an engineering approach to the problem. As is well known engineering problems often allow several or even multiple different solutions. Engineers are normally able to envisage several solutions and are in fact required to consider or partially develop several of them previous to the determination of the optimum one. The best solution is determined by comparing the candidate ones through multi-criteria analysis. Reaching an “optimum” solution requires, as a first step, conceiving and tentatively developing a set of alternative solutions. Similarly, reaching an “optimum” intervention requires first foreseeing and developing a set of alternative possibilities involving different strategies, techniques or materials. Engineers or architects involved in the design of repair or strengthening operations should always provide a set of alternative possibilities and then clearly describe the procedure and considerations which lead to the determination of the best one.

The possible impact of an intervention on a monument or building, in terms of loss or alteration of the original material and structural features, must always be investigated and quantified. As stated by the Recommendations, no action should be undertaken without ascertaining the likely benefit and harm to the architectural heritage. This procedure (even if described in qualitative terms) will permit comparisons between different solutions and will provide criteria for choosing the optimum one.
Choosing the best solution requires prioritizing the criteria stated in section 5.3. The aforementioned criteria (compatibility, durability, reversibility …) should be ordered according to their given importance and eventually qualified with a certain weight. In principle, it may seem adequate to give priority to the conditions of durability and compatibility of the repair materials or strengthening devices, since their failure may actually cause very severe problems to the original construction. There is very abundant information (and massive experience) on the bad consequences of using not very durable or “not-so-compatible” materials in restoration (Esponda, 2003). In practice, the preferred qualities are only given by historical or traditional materials. The use of some modern materials (such as steel or Portland cement and concrete) should be disregarded or restricted due to their very limited durability and likely compatibility problems (as already mentioned in section 5.3). The use of some more innovative materials (such as FRPs) should be also limited for the time being because of insufficient experience on their true durability.

Some of the conditions show a certain relationship and can be combined in a consistent way. For instance, reversibility and non-obtrusiveness might be required to a lesser extent if the materials are very durable and compatible with the existing ones. Accepting invasive solutions should convey the use of very durable (historically-durable) and fully compatible materials. Conversely, the replacement of “not-so-durable” repair materials or strengthening devices may be feasible if the solutions are fully reversible and non-obtrusive. Using steel (stainless steel) or FRP strengthening devices may be acceptable if their implementation is actually reversible and non-invasive.

The process leading to the design of an intervention must be based on the same scientific approach already used for the diagnosis and safety assessment. For instance, the selection of a possible strengthening method will always involve the acceptance of some hypothesis on its mechanical effects on the structure and the way it contributes to modify the response. These hypotheses should be recognized and explicitly stated. They should be validated by means of activities requiring, as for the diagnosis, some technical display (numerical simulation, laboratory experiments or the monitoring the structure after the execution of the intervention). In particular, the structural models elaborated for the diagnosis can be also used to simulate (and compare) possible solutions.

The perfect solution (i.e. the one perfectly complying with all the restoration criteria) may not exist. In other words, it should be recognized that any solution will produce some alteration. Even if totally harmless solutions do not exist, accepted solutions should be rigorously justifiable from the point of view of the concept (what the intervention is, the way it acts on the historical structure, what its beneficial effects are compared with its cost) and the method (how the best solution has been reached, how other solutions have been generated and how the comparison has been carried out).

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 optimum 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 (diagnosis, safety assessment) is finally to be invested in the design of adequate strengthening or repair actions.

The possible solutions must be objectively and accurately evaluated and eventually validated. This evaluation requires quantitative analyses by means of numerical or experimental methods for structural analyses. As mentioned, consistency requires that the same methods and tools previously used for the diagnosis and safety assessment also be used in the evaluation of the repair or strengthening actions.
The intervention will become part of the history of the structure. The designer must be aware of the “historical” meaning of his or her interaction with the building. Time is meaningful for both the original structure and the strengthened one. Intervention is a continuous process which accompanies the history of the building. Maintenance intervention begins immediately after the construction of the building; significant architectural or structural intervention may have been executed in historical times; modern intervention on a building may have (rarely) a more or less precise beginning, but it certainly will never finish. The designer must be aware that other future engineers or architects will keep on analysing and acting on the building; his or her work and actions will certainly influence not only the future response of the building but also the difficulties encountered and possible decisions to be taken by future technicians. The intervention must never be understood as a definitive action on the structure, but as an incremental contribution to the preservation of the building. Interventions should not block but permit further actions. “Blocking” solutions will hinder future action on the original structure and may force future actions to be designed as a “restoration of the restoration”. From this point of view, reversibility or removability are convenient conditions.

The intervention becomes part of the building and acts adding or subtracting value to it. A poor intervention, causing unnecessary and extensive alteration, will certainly subtract cultural or monumental value to the building (Fig. 3, left). An adequate intervention may even contribute with additional cultural value. Restoration and strengthening are (among other things) engineering problems admitting solutions of a certain merit. Successful solutions can receive admiration and become an example of well-doing because of their ability to reconcile technical requirements and respect; they can be admired because of their technical elegance or their scientific or technological merit. In these cases, it can be said that the solutions are actually adding value –after all, we admire ancient structures also because of their conjugation of architectural and technical merits within a given historical context. However, solutions must be judged on account of the complexity and nature of the engineering problems solved. A light, almost invisible, but effective intervention wisely solving a difficult problem should certainly deserve admiration. Very limited intervention, or even nil intervention adequately justified by a comprehensive investigation, constitutes also an optimum solution to the problem; in a way, it also adds value to the building. In the other extreme, a more intensive intervention whose need is justified after an honest and comprehensive research and whose practical implementation utilizes acceptable, even elegant technical solutions, should also be positively accepted. The positive or negative contribution of the intervention to the value of the building is an essential aspect to be taken into consideration in evaluating the adequacy of the possible solutions.

Cultural or social aspects are also to be taken into consideration. Solutions normally accepted in a certain country or culture may not be well received in other places because of different architectural tradition or understandings. For instance, ties placed between arch springings have been commonly used in Italy to strengthen churches or other buildings (Fig. 6, left). The same solution, proposed as a modern intervention, could be judged as inadequate or strange to local architecture, or leading to an excessive alteration of the inner space in some other countries.

It must be accepted that, in some cases, trying to convey all the required safety to a building may lead to a very severe transformation of its materials and structure, with an enormous loss of cultural value. In some cases, envisaging a satisfactory strengthening compatible with the value of the building may be very difficult or unaffordable. This can be the case of buildings that are very severely damaged or showing important structural or construction defects or are seismically weak. Rather than preserving, the intervention may lead to a virtual destruction of the values of the building. The problem, in these cases, is not in the risk of further damage or destruction if less extensive interventions are implemented (the other possible interventions being inherently destructive) but in the risks caused to people and particularly to possible visitors. These cases pose a very difficult problem –an inherent conflict- between true conservation and safety. Difficult decisions have to be taken which eventually 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.
6 CONCLUSIONS

The difficulties encountered in the study of ancient structures (in particular, the limitation of design codes and conventional methods for modern structures) can be overcome by adopting a flexible and broad approach encompassing both quantitative and qualitative evidence; at least four possible sources of knowledge (history, inspection, monitoring and structural analysis) can be considered and combined, as part of a scientific approach, to draw conclusions on the present condition, causes of damage or decay and need for intervention.

In spite of using a scientific approach, there is always some room for uncertainty and subjectivity. Two different causes contribute to this. Firstly, the data available are always limited because of both economical and technical reasons; additional assumptions and simplifications are often needed on the distribution and values of the mechanical properties of the materials. Secondly, no matter the effort invested in validating and calibrating a structural model, it will never simulate all the complexity involved in the real phenomena. In the studies of real constructions, the possible causes for uncertainty and subjectivity must be clearly stated with their possible influence on the reliability of the conclusions. Due to this, expertise and personal judgement form part of the analysis and are essential features for a successful diagnosis.

In the design of the intervention, the role of the engineer or architect consists of selecting an adequate solution which complies with the restoration criteria to an optimum extent. This can be carried out through an engineering approach based on considering a series of alternatives and then selecting the “optimum” one—that is to say, the one that, while complying with safety requirements, causes the least alteration to the original structure.

REFERENCES


