ICOMOS
INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

Contents

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PURPOSE OF THE DOCUMENT

Structures of architectural heritage, by their very nature and history (material and assembly), present a number of challenges in diagnosis and restoration that limit the application of modern legal codes and building standards. Recommendations are desirable and necessary to both ensure rational methods of analysis and repair methods appropriate to the cultural context.

These Recommendations are intended to be useful to all those involved in conservation and restoration problems, but cannot in anyway replace specific knowledge acquired from cultural and scientific texts.

The Recommendations presented in the complete document are in two sections: Principles, where the basic concepts of conservation are presented; Guidelines, where the rules and methodology that a designer should follow are discussed. Only the Principles have the status of an approved/ratified ICOMOS document.

Part I

PRINCIPLES

1 General criteria

1.1 Conservation, reinforcement and restoration of architectural heritage requires a multi-disciplinary approach.

1.2 The value and authenticity of architectural heritage cannot be assessed by fixed criteria because the respect due to each culture requires that its physical heritage be considered within the cultural context to which it belongs.

1.3 The value of each historic building is not only in the appearance of individual elements, but also in the integrity of all its components as a unique product of the specific building technology of its time and place. Thus the removal of the inner structures retaining only a façade does not satisfy conservation criteria.

1.4 Potential change of use must take into account all the conservation and safety requirements.

1.5 Any intervention to an historic structure must be considered within the context of the restoration and conservation of the whole building.

1.6 The peculiarity of heritage structures, with their complex history, requires the organisation of studies and analysis in steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions. To be both cost effective and ensure minimum impact on the architectural heritage it is often appropriate to repeat these steps in an iterative process.

1.7 No action should be undertaken without ascertaining the likely benefit and harm to the architectural heritage. Where urgent safeguard measures are necessary to avoid imminent collapse they should avoid minimal permanent alteration to the fabric.

2 Research and diagnosis

2.1 Usually a multidisciplinary team, chosen in relation to the type and scale of the problem, should work together from the beginning – i.e. from the initial survey of the site and the preparation of the investigation programme.

2.2 Usually we need first to analyse easily available data and information, only then if necessary drawing up a more comprehensive plan of activities appropriate to the structural problem.

2.3 A full understanding of the structural behaviour and material characteristics is essential for any conservation and restoration project. It is essential on the original state of the structure in its original and earlier states, on the techniques that were used in the and construction methods, on subsequent changes the phenomena that have occurred, and, finally, on its present state.

2.4 Archaeological sites present specific problems because structures have to be stabilised during excavation when knowledge is not yet complete. The structural responses to a "rediscovered" building may be completely different from those to an "exposed" building. Urgent site-structural-solutions, required to stabilise the structure as it is being excavated, must respect the concept form and use of the complete building.

2.5 Diagnosis is based on historical information and qualitative and quantitative approaches. The qualitative approach is based on direct observation of the structural damage and material decay as well as historical and archaeological research, while the quantitative approach requires material and structural tests, monitoring and structural analysis.

2.6 Before making a decision on structural intervention it is indispensable to first determine the causes of damage and decay, and then to evaluate the present level of structural safety.

2.7 The safety evaluation, which follows the diagnosis, is where the decision for possible intervention is determined, and needs to reconcile qualitative with quantitative analysis:

2.8 Often the application of the same safety levels used in the design of new buildings requires excessive, if not impossible, measures. In these cases other methods, appropriately justified, may allow different approaches to safety.

2.9 All the acquired information, the diagnosis, including the safety evaluation, and any decision to intervene should be set out in full in an “EXPLANATORY REPORT”.

3 Remedial measures and controls

3.1 Therapy should address root causes rather than symptoms.

3.2 Adequate maintenance can limit or postpone the need for subsequent intervention.

3.3 Safety evaluation and an understanding of the historical and cultural significance of the structure should be the basis for conservation and reinforcement measures.

3.4 No actions should be undertaken without demonstrating that they are indispensable.

3.5 Each intervention should be in proportion to the safety objectives, keeping intervention to the minimum necessary to guarantee safety and durability and with the least damage to heritage values.

3.6 The design of any intervention should be based on a full understanding of the kinds of action (forces, accelerations, deformations etc) that have caused the damage or decay and of those that will act in the future.

3.7 The choice between “traditional” and “innovative” techniques should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values, consistent with the need for safety and durability.

3.8 At times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest “an observational method”, i.e. an incremental approach, beginning with a minimum level of intervention, with the possible adoption of subsequent supplementary or corrective measures.

3.9 Where possible, any measures adopted should be “reversible” so that they can be removed and replaced with more suitable measures if new knowledge is acquired. Where they are not completely reversible, interventions should not compromise later interventions.

3.10 The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term effects, so that undesirable side effects are avoided.

3.11 The distinguishing qualities of the structure and its environment that derive from its original form and any significant subsequent changes should not be destroyed.

3.12 Each intervention should, as far as possible, respect the original concept and construction techniques and historical value of the structure and of the historical evidence that it provides.

3.13 Intervention should be the result of an integrated plan that gives due weight to the different aspects of architecture, structure, its function and installations.

3.14 The removal or alteration of any historic material or distinctive architectural features should be avoided whenever possible.

3.15 Repair is always preferable to replacement.

3.16 When imperfections and alterations have become part of the history of the structure, they should be maintained providing they do not compromise the safety requirements.

3.17 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.

3.18 Measures that are impossible to control during execution should not be allowed. Any proposal for intervention must be accompanied by a programme of monitoring and control to be carried out, as far as possible, while the work is in progress.

3.19 All control and monitoring activities should be documented and retained as part of the history of the structure.

Part II

GUIDELINES

1 General criteria

A combination of both scientific and cultural knowledge and experience is indispensable for the study of all architectural heritage. Only in this context can the guidelines help to the better conservation, strengthening and the restoration of buildings. The purpose of all studies, research and interventions is to safeguard the cultural and historical value of the building as a whole and structural engineering is the scientific support necessary to obtain this result.
Conserving architectural heritage usually requires a multidisciplinary approach involving a variety of professionals and organisations. These guidelines have been prepared to assist this work and facilitate communication between those involved.

Any planning for structural conservation requires both qualitative data, based on the direct observation of material decay and structural damage, historical research etc., and quantitative data based on specific tests and mathematical models of the kind used in modern engineering. This combination of approaches makes it very difficult to establish rules and codes. While the lack of clear guidelines can easily lead to ambiguities and arbitrary decisions, codes prepared for the design of modern structures are often inappropriately applied to historic structures. For example, the enforcement of seismic and geotechnical codes, can lead to drastic and often unnecessary measures that fail to take account of real structural behaviour.

The subjective aspects involved in the study and safety assessment of an historic building, the uncertainties in the data assumed and the difficulties of a precise evaluation of the phenomena, may lead to conclusions of uncertain reliability. It is important, therefore, to show clearly all these aspects, in particular the care taken in the development of the study and the reliability of the results, 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 and will facilitate the final judgement on the safety of the structure and the decisions to be taken.

The evaluation of a building frequently requires a holistic approach considering the building as a whole rather than just the assessment of individual elements.

2 Acquisition of data: Information and Investigation

2.1 Generally

The investigation of the structure requires an interdisciplinary approach that goes beyond simple technical considerations because historical research can discover phenomena involving structural behaviour while historical questions may be answered by considering structural behaviour. Therefore it is important that an investigating team be formed that incorporates a range of skills appropriate to the characteristics of the building and which is directed by someone with adequate experience.

Knowledge of the structure requires information on its conception, on its constructional techniques, on the processes of decay and damage, on changes that have been made and finally on its present state. This knowledge can usually be reached by the following steps:

- definition, description and understanding of the building's historic and cultural significance;
- a description of the original building materials and construction techniques;
- historical research covering the entire life of the structure including both changes to its form and any previous structural interventions;
- description of the structure in its present state including identification of damage, decay and possible progressive phenomena, using appropriate types of test;
- description of the actions involved, structural behaviour and types of materials;

A 'pre-survey' of both the site and the building should guide these studies.

Because these can all be carried out at different levels of detail it is important to establish a cost effective plan of activities proportional to the structure's complexity and which also takes into account the real benefit to be obtained from the knowledge gained. In some cases it is convenient to undertake these studies in stages beginning with the simplest.

2.2 Historical, structural and architectural investigations

The purpose of the historical survey is to understand the conception and the significance of the building, the techniques and the skills used in its construction, the subsequent changes in both the structure and its environment and any events that may have caused damage. Documents used for this should be noted.

The sources should be assessed for their reliability as a means of reconstructing the history of construction. Their careful interpretation is essential if they are to produce reliable information about the structural history of a building.

Assumptions made in the interpretation of historical material should be made clear. Particular attention should be paid to any damage, failures, reconstructions, additions, changes, restoration work, structural modifications, and changes of use that lead to the present condition.

It should be remembered that documents which may be used were usually prepared for purposes other than structural engineering and may therefore include technical information which is incorrect and/or may omit or misrepresent key facts or events which are structurally significant.

2.3 Survey of the structure

Direct observation of the structure is an essential phase of the study, usually carried out by a qualified team to provide an initial understanding of the structure and to give an appropriate direction to the subsequent investigations.

The main objectives include:

- identifying decay and damage,
- determining whether or not the phenomena have stabilised,
- deciding whether or not there are immediate risks and therefore urgent measures to be undertaken,
- identifying any ongoing environmental effects on the building.

The study of structural faults begins by mapping visible damage. During this process interpretation of the findings should be used to guide the survey, and the expert already developing an idea of the possible structural behaviour so that critical aspects of the structure may be examined in more detail. Survey drawings should map different kinds of materials, noting any decay and any structural irregularities and damage, paying particular attention to crack patterns and crushing phenomena.

Geometric irregularities can be the result of previous deformations, can indicate the junction between different building phases or alterations to the fabric.

It is important to discover how the environment may be damaging a building, since this can be exacerbated by poor original design and/or workmanship (e.g. lack of drainage, condensation, raising damp), the use of unsuitable materials and/or by poor subsequent maintenance.

Observation of areas where damage is concentrated as a result of high compression (zones of crushing) or high tensions (zones of cracking or the separation of elements) and the direction of the cracks, together with an investigation of soil conditions, may indicate the causes of this damage. This may be supplemented by information acquired by specific tests

2.4 Field research and laboratory testing

The schedule of tests should be based on a clear preliminary view of which phenomena are the most important to understand. Tests usually aim to identify the mechanical (strength, deformability, etc.), physical (porosity, etc.) and chemical (composition, etc.) characteristics of the materials, the stresses and deformations of the structure and the presence of any discontinuities within the structure.

As a rule, the schedule of tests should be divided into stages, starting with the acquisition of basic data, followed by a more detailed examination with tests based upon an assessment of the implications of the initial data.

Non-destructive tests should be preferred to those that involve any alterations to a structure; if these are not sufficient, it is necessary to assess the benefit to be obtained by opening up the structure in terms of reduced structural intervention against the loss of culturally significant material (a cost-benefit analysis).

Tests should always be carried out by skilled persons able to gauge their reliability correctly and the implication of test data should be very carefully assessed. If possible different methods should be used and the results should be compared. It may also be necessary to carry out tests on selected samples taken from the structure.

2.5 Monitoring

Structural observation over a period of time may be necessary, not only to acquire useful information when progressive phenomena is suspected, but also during a step-by-step procedure of structural renovation. During the latter, the behaviour is monitored at each stage (observational approach) and the acquired data used to provide the basis for any further action.
A monitoring system usually aims to record changes in deformations, cracks, temperatures, etc. Dynamic monitoring is used to record accelerations, such as those in seismic areas.

Monitoring can also act as an alarm bell.

The simplest and cheapest way to monitor cracks is to place a ‘tell-tale’ across them. Some cases require the use of computerised monitoring systems to record the data in real time.

As a general rule, the use of a monitoring system should be subjected to a cost-benefit analysis so that only data strictly necessary to reveal progressive phenomena are gathered.

3 The structural behaviour

3.1 General aspects

The behaviour of any structure is influenced by three main factors: the shape and the connections of the structure, the construction materials and the imposed forces, accelerations and deformations (the actions); these factors are here examined in detail

3.2 The structural scheme and damage

The structural behaviour depends on the characteristics of the materials, the dimensions of the structure, the connections between different elements, the soil conditions, etc.

The real behaviour of a building is usually too complex to fully model so that we are obliged to represent it with a simplified 'structural scheme', i.e. an idealisation of the building which shows, to the required degree of precision, how it resists the various actions.

The structural scheme shows how the building transforms actions into stresses and ensures stability.

A building may be represented by different schemes with different complexity and different degrees of approximation to reality.

The original structural scheme may have changed as a result of to damage (cracks, etc.), reinforcements, or other modifications of the building. The scheme used in the structural analysis is usually a compromise between one close to reality but too complex for calculation and one easy to calculate but too far from the reality of the building.

The scheme used has to take into account any alterations and weakening, such as cracks, disconnections, crushing, leanings, etc., whose effect may significantly influence the structural behaviour. These alterations may be produced either by natural phenomena or by human interventions. The latter includes the making of openings, niches, etc.; the elimination of arches, slabs, walls, etc., which can create unbalanced forces; increases in height of the structure, which can increase weights; excavations, galleries, nearby buildings, etc., which can reduce the soil bearing capacity.

3.3 Material characteristics and decay processes

Material characteristics (particularly strengths), which are the basic parameters for any calculation, may be reduced by decay caused by chemical, physical or biological action. The rate of decay depends upon the properties of the materials (such as porosity) and the protection provided (roof overhangs, etc.) as well as maintenance. Although decay may manifest itself on the surface, and so be immediately apparent from superficial inspection (efflorescence, increased porosity, etc.), there are also decay processes that can only be detected by more sophisticated tests (termite attack in timber, etc.).

3.4 Actions on the structure and the materials

'Actions' are defined as any agent (forces, deformations, etc.) which produce stresses and strains in the structure and any phenomenon (chemical, biological, etc.) which affects the materials, usually reducing their strength. The original actions, which act from the beginning of construction and the completion of the building (dead loads, for example), may be modified during its life and it is often these changes that produce damage and decay.

Actions have very different natures with very different effects on both the structure and the materials.

Often more than one action (or, change to the original actions), will have affected the structure and these must clearly be identified before selecting the repair measures.

Actions may be divided into mechanical actions that affect the structure and chemical and biological actions that affect the materials. Mechanical actions are either static or dynamic the former being either direct or indirect (see Table 1).

Table 1 – Classification of the different kinds of action on structures and their materials

<table>
<tr><td rowspan="3">1 - Mechanical actions –
acting on the structure</td><td rowspan="2">i) Static actions</td><td>a) Direct actions
(i.e. applied loads)</td></tr>
<tr><td>b) Indirect actions
(i.e. applied strains)</td></tr>
<tr><td colspan="2">ii) Dynamic actions
(imposed accelerations)</td></tr>
<tr><td colspan="3">2 i) Physical,
ii) Chemical and
iii) Biological actions –
acting on the materials</td></tr>
</table>

1 Mechanical actions acting on the structure produce stresses and strains in the material possibly resulting in visible cracking, crushing and movement. This can be static or dynamic

i) Static actions can be of two kinds:

a). Direct actions i.e. applied loads such as dead loads (weight of the building, etc.) and live loads (furniture, people, etc.). Changes, and mainly increases in loads, are sources of increased stresses and thus of damage to the structure

In some cases reductions in load can also be a source of damage to the structure.

b) Indirect actions (comprising deformations imposed on the boundaries of the structure, such as soil settlements, or produced within the body of the materials, such as thermal movements, creep in timber, shrinkage in mortar, etc. These actions, which may vary continuously or cyclically, produce forces only if deformations are not free to develop.

The most important and often most dangerous of all indirect actions are soil settlements (produced by change in the water table, excavations, etc.) which may create large cracks, leaning, etc.

A number of indirect actions are cyclic in nature, including temperature changes and some ground movements due to seasonal variation in ground water levels. The effects are usually cyclic too but it is possible for there to be progressive deformation or decay because each cycle produces some small but permanent change within the structure.

The temperature gradient between external surfaces and the internal body may cause

differential strains in the material and therefore stresses and micro-cracks, which further accelerate the decay.
Indirect actions can also be produced by the progressive reduction of the stiffness of elements of an indeterminate (hyperstatic) structure (weakening, decay processes, etc.), resulting in a redistribution of stresses.

ii) Dynamic actions are produced when accelerations are transmitted to a structure, due to earthquakes, wind, hurricanes, vibrating machinery, etc.
The most significant dynamic action is usually caused by earthquakes. The intensity of the forces produced is related to both the magnitude of the acceleration and to the natural frequencies of the structure and its capacity to dissipate energy. The effect of an earthquake is also related to the history of previous earthquakes that may have progressively weakened the structure.

2) Physical, chemical, and biological actions are of completely different nature from those described above and act on the materials changing their nature often resulting in a different kind of decay and in particular affecting their strength.
Material properties may change over time due to natural processes characteristic of the material, such as slow hardening of lime mortar or slow internal decay.
These actions may be influenced and accelerated by the presence of water (rain, humidity, ground water, wetting and drying cycles, organic growth, etc.), variations in temperature (expansion and contraction, frost action, etc.) and micro-climatic conditions (pollution, surface deposition, changes in wind speeds due to adjacent structures, etc.). Fire can be considered as an extreme change of temperature.
A very common action is the oxidation of metals. This may be visible on the surface or may be occurring to metal reinforcing placed inside another material and therefore only apparent through secondary effects, such as splitting and spalling of the other material.
Chemical changes may occur spontaneously because of the inherent characteristics of the material or be produced as a result of external agents, such as the deposition of pollutants, or the migration of water or other agents through the material.
Biological agents in timber are often active in areas not easily inspected.

4 Diagnosis and safety evaluation

4.1 General aspects

Diagnosis and safety evaluation of the structure are two consecutive and related stages on the basis of which the effective need for and extent of treatment measures are determined. If these stages are performed incorrectly, the resulting decisions will be arbitrary: poor judgement may result in either conservative and therefore heavy-handed conservation measures or inadequate safety levels.

Evaluation of the safety of the building should be based on both qualitative (as documentation, observation, etc.) and quantitative (as experimental, mathematical, etc.) methods that take into account the effect of the phenomena on structural behaviour.

Any assessment of safety is seriously affected by two types of problem:

- the uncertainty attached to data (actions, resistance, deformations, etc.), laws, models, assumptions, etc. used in the research;
- the difficulty of representing real phenomena in a precise way.

It therefore seems reasonable to try different approaches, each giving a separate contribution, but which when combined produce the best possible ‘verdict’ based on the data at our disposal.

When assessing safety, it is also necessary to include some indication, even if only qualitative, of the reliability of the assumptions made, of the results and of the degree of caution implicit in the proposed measures.

Modern legal codes and professional codes of practice adopt a conservative approach involving the application of safety factors to take into account the various uncertainties. This is appropriate for new structures where safety can be increased with modest increases in member size and cost. However, such an approach is not appropriate in historic structures where requirements to improve the strength may lead to the loss of historic fabric or to changes in the original conception of the structure. A more flexible and broader approach needs to be adopted for historic structures to relate the remedial measures more clearly to the actual structural behaviour and to retain the principle of minimum intervention.

The verdict on a structure's safety is based on an evaluation of the results obtained from the three diagnostic procedures that will be discussed below. These bear in mind that the qualitative approach plays a role as important as the quantitative approach.

It also has to be noted that the safety factors established for new buildings take into account the uncertainties of construction. In existing buildings these uncertainties may be reduced because the real behaviour of the structure can be observed and monitored. If more reliable data can be obtained, reduced theoretical factors of safety do not necessarily correspond to a real reduced safety. However there are cases where the contrary is true and data are more difficult to obtain for historic structure. (This is dealt with in more detail in paragraphs 4.3.1 & 4.3.4 below)

4.2 Identification of the causes (Diagnosis)

The diagnosis is to identify the causes of damage and decay, on the basis of the acquired data. This comes under three headings:

- Historical analysis (see 4.3.2.)
- Qualitative analysis (see 4.3.3)
- Quantitative analysis, which includes both mathematical modelling (see 4.3.4) and testing (see 4.3.5).

The diagnosis is often a difficult phase, since the data available usually refer to the effects, while it is the cause or, as it is more often the case, the several concomitant causes that have to be determined. This is why intuition and experience are essential components in the diagnostic process. A correct diagnosis is indispensable for a proper evaluation of safety and a rational decision on the treatment measures to be adopted.

4.3 Safety evaluation

4.3.1 The problem of safety evaluation

Safety evaluation is the next step towards completion of the diagnostic phase. Whilst the object of diagnosis is to identify the causes of damage and decay, safety evaluation must, determine whether or not the safety levels are acceptable, by analysing the present condition of both structure and materials. The safety evaluation is therefore an essential step in the project of restoration because this is where decisions are taken of the need for and the extent of any remedial measures.

However, safety evaluation is also a difficult task because methods of structural analysis used for new construction may be neither accurate nor reliable for historic structures and may result in inappropriate decisions. This is due to such factors as the difficulty in fully understanding the complexity of an ancient building or monument, uncertainties regarding material characteristics, the unknown influence of previous phenomena (for example soil settlements), and imperfect knowledge of alterations and repairs carried out in the past. Therefore, a quantitative approach based on mathematical models cannot be the only procedure to be followed. As with the diagnosis, qualitative approaches based on historical research and on observation of the structure should also be used. A fourth approach based on specific tests may also be useful in some situations.

Each of these approaches, which are discussed below, can inform the safety evaluation, but it is the combined analysis of the information obtained from each of them, which may lead to the 'best judgement'. In forming this judgement both quantitative and qualitative aspects should be taken into account having been weighed on the basis of the reliability of the data and the assumptions made. All this needs to be set out in the EXPLANATORY REPORT already discussed.

It must be clear, therefore, that 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 because, as already noted, they can be unreliable and inappropriate.

Similar procedures have to be followed to evaluate the safety levels after the design of some kinds of intervention (see paragraph 5) in order to assess their benefits and to ensure that their adoption is appropriate (neither insufficient nor excessive).

4.3.2 Historical analysis

Knowledge of what has occurred in the past can help to forecast future behaviour and can be a useful indication of the level of safety provided by the present state of the structure. History is the most complete, life-size, experimental laboratory. It shows how the type of structure, building materials, connections, joints, additions and human alterations have interacted with different actions, such as overloads, earthquakes, landslides, temperature variations, atmospheric pollution, etc., perhaps altering the structure's original behaviour by causing cracks, fissures, crushing, movement out-of-plumb, decay, collapse, etc. The structural task is to discard superfluous information and correctly interpret the data relevant to describing the static and dynamic behaviour of the structure.

Although satisfactory behaviour shown in the past is an important factor for predicting the survival of the building in the future, it is not always a reliable guide. This is particularly true where the structure is working at the limit of its bearing capacity and brittle behaviour is involved (such as high compression in columns), when there are significant changes in the structure or when repeated actions are possible (such as earthquakes) that progressively weaken the structure.

4.3.3 Qualitative analysis

This approach is based on the comparison between the present condition of structure and that of other similar structures whose behaviour is already understood. Experience gained from analysing and comparing the behaviour of different structures can enhance the possibility of extrapolations and provide a basis for assessing safety.

This approach (known in philosophical terms as inductive procedure) is not entirely reliable because it depends more upon personal judgement than on strictly scientific procedures. Nonetheless, it can be the most rational approach where there are such uncertainties inherent in the problems that other approaches only give the appearance of being more rigorous and reliable.

Having observed the behaviour of different structural types in varying stages of damage and decay caused by different actions (earthquakes, soil settlement, etc.), and having acquired experience of their soundness and durability, it is possible to extrapolate this knowledge to predict the behaviour of the structure under examination. The reliability of the evaluation will depend on the number of structures observed and, therefore, on the experience and skills of the individuals concerned. An appropriate programme of investigation and monitoring of progressive phenomena can increase its reliability.

4.3.4 The analytic approach

This approach uses the methods of modern structural analysis which, on the basis of certain hypotheses (theory of elasticity, theory of plasticity, frame models, etc.), draws conclusions based on mathematical calculations. In philosophical terms it is a deductive procedure. However, the uncertainties that can affect the representation of the material characteristics, and the imperfect representation of the structural behaviour, together with the simplifications adopted may lead to results that are not always reliable, even very different from the real situation. The essence of the problem is the identification of meaningful models that adequately depict both the structure and the associated phenomena with all their complexity making it possible to apply the theories at our disposal.

Mathematical models are the common tools used in structural analysis. Models describing the original structure, if appropriately calibrated, allow comparison of the theoretical damage produced by different kinds of action with the damage actually surveyed, providing a useful tool for identifying the causes of such damage. Mathematical models of both the damaged and the reinforced structure will help to evaluate present safety levels and to assess the benefits of proposed interventions.

Structural analysis is an indispensable tool. Even when the results of calculations and analysis cannot be precise, they can indicate the flow of the stresses and possible critical areas. But mathematical models alone are usually not able to provide a reliable safety evaluation. Grasping the key issues, and correctly setting the limits for the use of mathematical techniques, depends upon the expert's use of his scientific knowledge.

Any mathematical model must take into account the three aspects described in section 3: the structural scheme, the material characteristics and the actions to which the structure is subjected.

4.3.5 The experimental approach

Specific tests (such as test loading a floor, a beam, etc.) will provide a direct measure of safety margins, even if they are applicable only to single elements rather than to the building as a whole.

4.4 Decisions and explanatory report

The judgement on a structure's safety is based on the results of the three (or four) main approaches described above (the fourth approach having a limited application). When analysis shows inadequate safety levels, it should be checked to see if it has used insufficiently accurate data or excessively conservative values. This might lead to the conclusion that more investigation is necessary before a diagnosis can be made.

Because qualitative judgements may play a role as important as quantitative data, the safety assessment and the consequent decisions on intervention should be set out in the EXPLANATORY REPORT (already referred to) where all the considerations which have led to the final evaluation and decisions are clearly explained. This must take into account both the degree of accuracy and of caution underlying each decision and be based on logically consistent reasoning.

Time factors must be considered in the EXPLANATORY REPORT, because a decision to undertake immediate measures, or a decision to accept the status quo, are simply the two extremes in a scale of choices. The alternatives are often to strengthen the structure on the basis of present knowledge or to extend the research to obtain more complete and reliable data in the hope of reducing any interventions. However some deadline must be set for implementing the decisions, bearing in mind that safety is of probabilistic nature with the likelihood of damage or failure increasing the longer remedial actions is delayed.

The factors underlying the setting of a deadline will depend essentially on three types of phenomena:

- continuous processes (for example decay process, slow soil settlements, etc.) which will eventually reduce safety levels to below acceptable limits, so that measures must be taken before that occurs;
- phenomena of cyclical nature (variation in temperature, moisture content, etc.) that will produce increasing deterioration;
- phenomena that can suddenly occur (such as earthquakes, hurricanes, etc.). The probability of these occurring at any defined level increases with the passage of time, so that the degree of safety to be provided can theoretically be linked to the life expectancy of the structure (for example, it is well known that to protect a building against earthquakes for five centuries it is necessary to assume highest actions than those assumed to protect the same building for one century).

5 Structural damage, materials decay and remedial measures

5.1 General aspects

This section considers decision procedures involved in both the investigation of a structure and the selection of remedial measures to be applied. In the following paragraphs some examples of the most frequent damage and repair methods for the main structural materials are outlined, without pretending to provide an exhaustive review of the many possible solutions published elsewhere.

Structural damage occurs when the stresses produced by one or more action (see 3.4) exceed the strength of the materials in significant zones, either because the actions themselves have increased or because strength has been reduced. Substantial changes in the structure, including partial demolition, may also be a source of damage.

Manifestation of damage is related to the kind of actions and construction of material. Brittle materials will fail with low deformations while ductile materials will exhibit considerable deformation before failure.

The appearance of damage, and in particular cracks, is not necessarily an indication of risk of failure in a structure because cracks may relieve stresses that are not essential for equilibrium (for example, certain kinds of cracks produced by soil settlements) and may, through changes in the structural system, allow a beneficial redistribution of the stresses.

Damage may also occur in non-structural elements, e.g. cladding or internal partitions, as a result of stresses developed within those elements due to deformations or dimensional changes within the structure.

Material decay is brought about by chemical, physical and biological actions and may be accelerated when these actions are modified in an unfavourable way (for example by pollution, etc.). The main consequences are the deterioration of the surfaces, the loss of material and, from the mechanical point of view, a reduction of strength. Stabilisation of the material characteristics is therefore an important task for the conservation of historic buildings; a programme of maintenance is an essential activity because while preventing or reducing the rate of change may be possible it is often difficult or even impossible to recover lost material properties.

5.2 Masonry building

The term masonry here refers to stone, brick and earth based construction (i.e. adobe, pisé de terre, cobb, etc.). Masonry structures are generally made of materials that have a very low tensile strength and may easily show cracking within, or separation between elements. Nevertheless, these signs are not necessarily an indication of danger as masonry structures are intended to work mainly in compression.

The preliminary analysis of masonry requires the identification of the characteristics of the constituents of this composite material: the stones (limestone, sandstone, etc) or bricks, (fired or sun dried, etc.), and the type of mortar (cement, lime, etc.). It is also necessary to know how the elements are bonded (dry joints, mortar joints etc) and the way in which they are geometrically related to each other. Different kinds of tests may be used to ascertain the composition of the wall (endoscopic tests, etc.)

Masonry structures commonly rely upon the effect of the floors or roofs to distribute lateral loads and so ensure their overall stability. It is important to examine the disposition of such structures and their effective connection to the masonry. It is also necessary to understand the sequence of construction because the different characteristics of different periods of masonry can affect the overall behaviour of the structure.

The main causes of damage or collapse are vertical loads resulting in crushing, buckling, brittle failure, etc. These situations are particularly dangerous because they usually happen with small deformations and few visible signs. Lateral forces and their effects are relevant in seismic areas, in tall constructions, and where there is the thrust of arches or vaults.

Particularly attention has to be paid to large walls constructed of different kinds of material. Such walls include cavity walls, rubble filled masonry walls and veneered brick walls which have a poor quality core. Not only may the core material be less capable of carrying load but it can also produce thrusts on the faces. In this type of masonry the external leaves can separate from the core so that it is necessary to determine whether the facing and the core are acting together or separately. The latter condition is usually dangerous because the faces may become unstable.

Compressive stresses close to the capacity of the materials can cause vertical cracks as the first sign of damage eventually leading to large lateral deformations, spalling, etc. The extent to which these effects become visible depends upon the material's characteristics and in particular its brittleness. These effects can develop very slowly (even over decades) or quickly, but stresses close to the ultimate strength present a high risk of collapse even if the loads remain constant.

An analysis of the distribution of stresses is useful to identify the causes of the damage. To understand the cause of damage (diagnosis) it is first necessary to determine the levels and distribution of stress, even if approximately, because they are usually very low, so that some errors do not significantly affect the safety margin. A detailed visual inspection of the crack pattern may provide an indication of load paths within a structure.

When the stresses in significant areas are close to the ultimate strength it is necessary to carry out either a more accurate structural analysis or specific tests on the masonry (flat jack test, sonic test, etc.) to provide a more accurate assessment of the strength.

In-plane lateral loads can cause diagonal cracks or sliding. Out-of-plane or eccentric loads may cause separation of the leaves in a multi-leaf wall or rotation of an entire wall about its base. Where the latter occurs, horizontal cracks at the base might be seen before overturning occurs.

Various interventions to strengthen a wall include:

- repointing of the masonry, consolidation of the wall with grout,
- vertical longitudinal or transverse reinforcement,
- removal and replacement of decayed material,
- dismantling and rebuilding, either partially or completely.

The selection of appropriate fluid mortars (lime, cement, resins, special products, etc.) injected to consolidate the masonry in order to address problems of cracking and decay depends upon the characteristics of the materials. Particular attention has to be given to the compatibility between original and new materials. Cements containing salts can only be used when there is no risk of damage to the masonry and particularly its surfaces. In walls with gypsum-containing mortars the reaction between gypsum and cement-minerals, results in the formation of salts that sooner or later will cause damage. There may be a problem of leaching of soluble salts from the mortar resulting in efflorescence on the surface of brickwork (particularly risky when there are historic plasters or frescoes).

As an alternative to the consolidation of the material itself, ties made of appropriate materials can be used to improve the load-bearing capacity of the masonry.

A number of products are available for consolidation of surfaces that have no plaster to protect them. However, these products are seldom completely effective and particular attention has to be paid to possible side effects.

Typical to masonry structures are arches and vaults. These rely on their curvature and the thrust at the abutments to reduce or eliminate bending moments, thus allowing the use of materials with low tensile strength. Their load bearing capacity is excellent and it is the movement of the abutments, that introduces bending moments and tensile stresses, leading to opening of the joints and possible collapse.

The formation of thin cracks is quite normal to the behaviour of some vaulted structures.

Structural distress may be associated with poor execution, (poor bonding of units, low material quality, etc.), inappropriate geometry for the load distribution, or inadequate strength and stiffness of components that must resist the thrusts (chains, shoulders).

When the construction material has very low strength (as in structures made of irregular stones with a lot of mortar) it is possible for parts of the vaults to become detached in the zones where the compression is lower or where there are tension stresses, possibly leading to progressive collapse.

The relationship between load distribution and geometry of the structure needs to be carefully considered when loads (especially heavy dead loads) are removed or added to arches or vaulted masonry structures.

The main repair measures are based on recognition of the above points, i.e. the addition of new tie rods (usually at the spring level in the vaults, or along parallel circles in the domes) construction of buttresses; correction of the load distribution (in some cases by adding loads);

High rise buildings as towers, bell towers, minarets, etc., are characterised by high compression stresses and present problems similar to those of pillars and columns. In addition, these structures are further weakened by imperfect connections between the walls, by alterations such as the making or closing of openings, etc.
Diaphragms, horizontal tie bars and chains can improve the ability to resist gravity loads.

5.3 Timber

Wood has been used in both load-bearing and framed structures, in composite structures of wood and masonry and to form major elements of load-bearing masonry structures.

Its structural performance is affected by species, growth characteristics, and by decay. Preliminary operations should be identification of the species, which are differently susceptible to biological attack, and the evaluation of the strength of individual members which is related to the size and distribution of knots and other growth characteristics. Longitudinal cracks parallel to the fibres due to drying shrinkage are not dangerous when their dimension are small.

Durability may be affected by the methods of harvesting, seasoning and conversion, which may have been different at different times.

Fungal and insect attack are the main sources of damage. These are linked to a high moisture content and temperature. The in-service moisture content should be measured as an indication of vulnerability to attack. Poor maintenance of buildings or radical changes in the internal conditions are the most common causes of timber decay.

Contact with masonry is often a source of moisture. This may occur either where the masonry supports the timber or where timber has been used to reinforce the masonry.

Because decay and insect attack may not be visible at the surface, methods, such as micro-drilling, are available for the examination of the interior of the timber.

Chemical products can protect the wood against biological attack. For example, in floors or roofs the ends of the beams inserted into masonry walls may need to be protected.

Where either reinforcing materials or consolidants are introduced, their compatibility with the timber structure must be verified. For example steel fasteners may be susceptible to corrosion in association with some species and so stainless steels should be used. Interventions should not restrict the evaporation of moisture from the timber.

To dismantle and reassemble timber structures is a delicate operation because of the risk of damage. There is also the possible loss of associated materials that are of historical significance. However, because many timber structures were originally prefabricated, there are circumstances where either partial or complete dismantling may facilitate an effective repair.

Timber is often used to form framed and trussed structures where the main problems are related to local failure at the nodes. Common remedial measures consist in reinforcing the nodes or adding supplementary diagonal elements when it is necessary to improve the stability against lateral forces.

5.4 Iron and steel

It is necessary to distinguish between cast iron, wrought iron and steel structures. The first is not only weak in tension but may have built in stresses resulting from the casting process. This is a brittle material and if subject to tensile stresses may fracture without warning. The strength of individual members can be adversely affected by poor workmanship in the foundry.

Iron and steel are alloys and their susceptibility to corrosion depends upon their composition. Corrosion is always accompanied by an increase in the volume of material that may give rise to stresses in associated materials; for example the splitting of stone or concrete as a result of the corrosion of inserted iron bars or cramps.

The most vulnerable aspects of steel structures are their connections where stresses are generally highest, especially at holes for fasteners. Bridges or other structures subjected to repeat loading might be subject to fatigue failure.
Therefore in riveted and bolted connections it is very important to check cracks starting from the holes. Fracture analysis enables the remaining life-span of the structure to be assessed.

Protection against corrosion of iron and steel requires first the elimination of rust from the surfaces (by sand blasting, etc.) and then painting the surface with an appropriate product.
Heavily damaged and deformed iron or steel structures usually can't be repaired. Strengthening of weak structures can often be achieved adding new elements, paying particular attention when welding.

5.5 Reinforced concrete

Reinforced and prestressed concrete are the basic materials of many modern buildings that are now recognised as being of historic importance. However, at the time of their construction a full understanding of the performance of these materials was still developing, so that they may present special problems of durability (poor cement mixes, inadequate cover to the reinforcement, etc.).
The most common problems involve the carbonation of the concrete (which hardens but also becomes more brittle), reducing its capacity to protect the steel. Reinforced concrete exposed to chlorides (either in marine locations or from road salting) is particularly susceptible to corrosion of the steel.

Corrosion of the steel results in spalling of the concrete. To consolidate a reinforced concrete element thus affected usually requires the removal of the deteriorated concrete (water jet, etc.), the cleaning of the steel, the addition of new reinforcement and the rebuilding of the surface, often using special concretes.

Part III

GLOSSARY

Action n. - Any agent (forces, deformations, etc.) which directly or indirectly produces stresses and/or strains into a building structure and any phenomenon (chemical, biological, etc.) which affects the materials of which the building structure is composed. The different categories of actions and their definitions are given in the "Guidelines".

Adobe n. - Adobe are bricks made from clay and simply dried in the sun. Some organic materials like straw or animal excrement can be used to improve durability or reduce shrinkage.

Anamnesis n. - The account of the case history of a building including past traumas, interventions, modifications, etc. The research to acquire this information prior to examination. This is the first step prior to diagnosis. See *Control, Diagnosis,* and *Therapy.*

Architectural Heritage n.- Buildings and complex of buildings (towns, etc.) of historical value. See *Building.*

Brick n.- A brick is a masonry unit usually made of clay which can be fired or simply dried in the sun

Brick Masonry n.- Brick masonry is a composite structure or material made of alternating brick courses set in mortar.

Building n. - Something that is built. When used in context of these "Recommendations", the term encompasses churches, temples, bridges, dams, and all construction works. Also referred to as Architectural Heritage.

Control n. - A standard of comparison for checking the results of an experiment. To verify and regulate the efficiency of an enacted therapy through tests, monitoring and examination. See *Anamnesis, Diagnosis,* and *Therapy.*

Conservation n. – Operations which maintain the building as it is today, even if limited interventions are accepted to improve the safety levels.

Cost Benefit analysis - Costs and benefits refer to general rather than monetary terms. Costs can be measured also in the potential loss of fabric due to the invasiveness of the therapy, and benefits can be those gained by the therapy as well as knowledge that will prove useful in the future. This term should not to be interpreted as "value engineering".

Damage n. - Change and worsening of the structural behaviour produced by mechanical actions or/and by the reduction of the strength.
Reduction of the mechanical bearing capacity related to the breakdown of a structural system. See *Decay* and *Structure.*

Decay n. – Change and worsening of the materials characteristics produced by chemical or biological actions. Chemical deterioration related to the breakdown of the materials of which a structural system is composed. Loss of quality, wasting away, decayed tissue. See *Damage.*

Diagnosis n. - The act or process of identifying or determining the nature and cause of damage and decay through, observation, investigation (including mathematical models) and historical analysis, and the opinion derived from such activities. See *Anamnesis, Control,* and *Therapy.*

Examination n. - The visual part of an investigation that excludes material testing, structural analysis, structural testing, and other more sophisticated investigative techniques.
See Investigation *Material Testing, Structural Analysis* and *Structural Testing.*

Explanatory Report - A report that specifically defines the subjective aspects involved in a safety assessment, such as uncertainties in the data assumed, and the difficulties in a precise evaluation of the phenomena that may lead to conclusions of uncertain reliability.

Fabric n. - The structural and material parts that make up the building (frames, walls, floors, roof, etc.)

Fired bricks - A fired brick is ceramic material obtained by preparation, moulding (or extrusion) of raw material (clay) and subsequent drying and firing at an appropriate temperature.

Geometrical Survey - Survey sheets. Measured drawings (plans, elevations, sections, etc.) where the geometry of the building is identified.

Heritage Value - Architectural, cultural, and/or historic value ascribed to a building or site. Heritage value may have varying definitions and importance from culture to culture.

Historical Approach - Evaluation based upon historical research and past experience. See *Qualitative Approach* and *Quantitative Approach.*

Holistic adj. - Emphasizing the importance of the whole and the interdependence of its parts.

Intervention n. - The physical intrusion upon a building during a diagnosis, or its therapy.

Investigation n. - A systematic and detailed evaluation of a building that can include examination, material testing, structural analysis, and structural testing. See *Diagnosis, Examination, Material Testing, Structural analysis,* and *Structural Testing.*

Maintenance - A series of activities finalised to the conservation of the asset

Material Testing - Laboratory or field testing of materials (physical, chemical, porosity, accelerated weathering, etc.).

Mortars – A mortar is a mix of one or more binders, aggregates and water. Sometimes additivies in certain proportions are included to give the mixture appropriate consistency and workability in the fresh state and adequate physical-mechanical properties when hardened.

Multi leaf masonry – Masonry made of leaves of different constitution. (The most common is the three leaves masonry made of two external faces and an inner rubble core.)

Natural stones - Natural stones have been formed by geological processes. They consist of mixtures of minerals.
Natural stones can be grouped according to their origin into magmatic, metamorphous and sedimentary stones (sandstone, limestone, etc.). Natural stones differ by origin, if their composition has not been altered by man.

Observational Method - An increment approach to intervene or to strengthen, starting from a minimum level of intervention, with possible subsequent adoption of a series of corrective measures.

Quantitative Approach - Evaluation based on analytic or scientific methods such as testing, calculations, and mathematical modeling. See *Historical Approach* and *Qualitative Approach.*

Rehabilitation – Process to bring a building to a new use or function, without alterating the portions of the building that are significant to its historical value.

Repointing - Result of repair or restoration on a deteriorated joint. It can be homogeneous to the existing joint or made of different material (e.g. cement of polymer).

Restoration – Process of recovering the form of a building as it appeared at a particular period of time by means of removal of additional work or by replacement of missing later work.

Safety Evaluation (assessment) - Evaluation of the safety margins of a structure with regard to heavy damage, partial or total collapse. See *Historical approach, Qualitative Approach, Quantitative Approach.*. the opposite of safety is risk.

Strengthening – Interventions to increase the bearing capacity of a structure.

Structural Analysis - Calculations, computations, computer analysis using mathematical models.

Structural scheme – An approximate representation (or model) of the structure, different, but close to the reality.

Structural Testing - Laboratory or field testing of structures (assembly and component testing, floor loading, shaking-tables, etc.).

Structural Typology - The types of structures interpreted as regards their structural behaviour and their capacity to bear loads.

Structure n. – The part of a building which provides the bearing capacity, sometimes coincident with the building itself**.**

Tell-tale - A device fixed across a crack in a masonry structure to indicate movement.

Therapy - The choice of remedial measures (reinforcement, strengthening, replacement, etc.) in response to diagnosis. See *Anamnesis, Control,* an d *Diagnosis.*