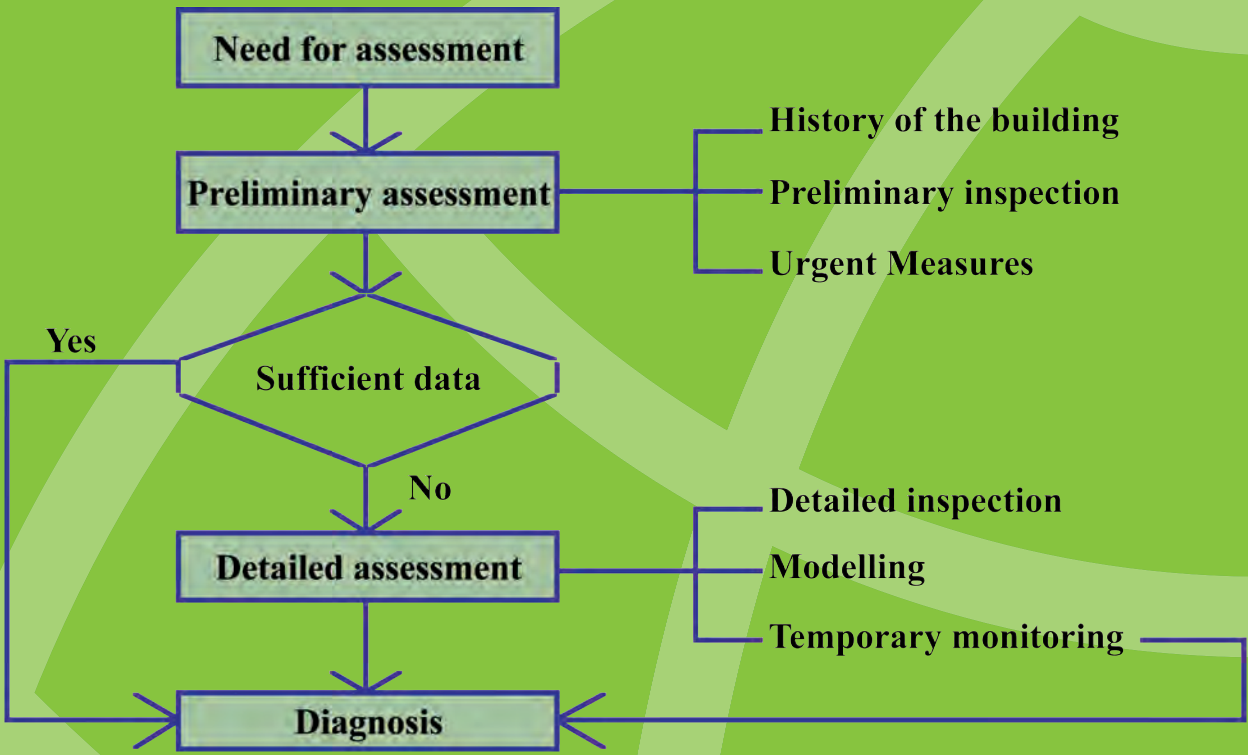

Guide for the Structural Rehabilitation of Heritage Buildings

CIB Publication 335
ISBN: 978-90-6363-066-9

GUIDE FOR THE
STRUCTURAL REHABILITATION OF HERITAGE BUILDINGS

June, 2010

GUIDE FOR THE
STRUCTURAL REHABILITATION OF HERITAGE BUILDINGS

Prepared by CIB Commission

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GUIDE FOR THE
STRUCTURAL REHABILITATION OF HERITAGE BUILDINGS

PREFACE

Rehabilitation of heritage buildings has become an issue of great importance around the world, particularly in the most developed societies. It is the result of the need to improve existing buildings for new conditions of use, and also of the recognition of the importance of conservation of the architectural heritage.

Existing buildings are subjected to processes of degradation with time, which leads to a situation in which they became not able to fulfil the purpose for which they were built. Sometimes, there is also the need to improve the conditions offered by existing buildings or to adapt them to new functions.

Furthermore, in the most developed societies, as they progress, the feeling grows that it is necessary to maintain the existing architectural heritage. As a kind of counterpoint to the changes caused by rapid technological evolution, the feeling grows of keeping the existing built environment and passing it on to future generations. Rehabilitation of heritage buildings is a way of sustainable development and also an act of culture.

The most sensitive aspect of the rehabilitation of existing buildings is their structural rehabilitation, i.e., their structural safety. However, assessment of the structural safety of existing buildings is, in general, a complex task, because the methodologies used differ from those adopted in the design of new structures. Furthermore, the eventual strengthening of existing buildings can conflict with their cultural value.

Therefore, the type of intervention on a heritage building will depend on its cultural value, ranging from simple maintenance, where the objective is not to change the cultural value of the building, to complex rehabilitation, when it is intended to improve the performance of the building.

Being aware of the importance of the issue, CIB Commission W023 - Wall Structures has decided, at its meeting in Amsterdam, in 2004, to develop a document containing guidance for the rehabilitation of heritage buildings, with a special emphasis on the assessment of the structural safety: *Guide for the Structural Rehabilitation of Heritage Buildings*.

The Guide has as its basis the CIB Publication *Structural Assessment and Redesign of Masonry Wall Structures*, edited in1992, being now the focus the masonry buildings with significant cultural value. It has been developed in line with the Publication of ICOMOS (ISCARSAH) *Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage*, approved in 2003, which philosophy and main concepts and have been adopted.

The Guide has been prepared by an Editing Panel consisting of CIB W023 Commission members and invited experts in this field, convened by the Commission Coordinator, with contributions coming from other Commission members. Thanks are due to all of them.

Thanks are also due to the Barry Haseltine, Honorary Commission member, for the revision of the English language of the text.

As Coordinator of CIB Commission W023-Wall Structures, I hope that this Guide will be fruitful and will help on structural rehabilitation of heritage buildings around the world.

Lisbon, June, 2010

S. Pompeu Santos

CIB W023 Commission Coordinator

GUIDE FOR THE STRUCTURAL REHABILITATION OF HERITAGE BUILDINGS

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STRUCTURAL REHABILITATION OF HERITAGE BUILDINGS

1 INTRODUCTION

Heritage buildings are defined as existing buildings with significant cultural value to society. Developed societies ascribe cultural value to existing buildings, so they are seen as cultural heritage. In general terms, it can be said that the cultural value of an existing building is as high as it is old.

Rehabilitation of heritage buildings has become an issue of great importance around the world, particularly in the most developed societies. It is the result of the need to improve existing buildings for new conditions of use, and also of the recognition of the importance of conservation of the architectural heritage.

Existing buildings are subjected to processes of degradation with time, which leads to a situation in which in which they became not able to fulfil the purpose for which they have been built. Sometimes, there is also the need to improve the conditions offered by the existing buildings or to adapt them to new functions.

Furthermore, in the most developed societies, as they progress, grows the feeling that it is necessary to maintain the existing building heritage. With the changes provoked by rapid technological evolution, as a kind of counterpoint, grows the feeling of to keep the existing built environment and to pass it on to future generations. Rehabilitation of heritage buildings is a way of sustainable development and also an act of culture.

The most sensitive aspect of the rehabilitation of existing buildings is their structural rehabilitation, i.e., that which is related to their structural safety. However, the assessment of the structural safety of existing buildings is, in general, a complex task, because the methodologies used differ from those adopted in the design of new structures. Furthermore, the eventual strengthening of existing buildings can conflict with their cultural value.

Therefore, the type of intervention on the heritage building will depend on the existing situation of the building, and also, on its cultural value, going from simple maintenance, where the objective is not to change the cultural value of the building, to deep rehabilitation, when it is intended to improve the performance of the building.

Being aware of the importance of the issue, CIB Commission W023 - Wall Structures has decided to develop a document with guidance for the interventions of rehabilitation of heritage buildings, with a special emphasis on the assessment of the structural safety, having the title: *Guide for the Structural Rehabilitation of Heritage Buildings*.

The Guide has as its basis the CIB Publication *Structural Assessment and Redesign of Masonry Wall Structures*, edited in1992, being now the focus for masonry buildings with significant cultural value. It has been developed in line with the Publication of ICOMOS (ISCARSAH) *Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage*, approved in 2003, which philosophy and main concepts have been adopted.

2 GENERAL ASPECTS

2.1 The need for intervention

As referred to above, heritage buildings are considered to be existing buildings with significant cultural value; they can be buildings, towers, bridges, etc. They are mostly made of masonry and timber, sometimes with elements in steel or iron.

The need for structural rehabilitation of heritage buildings is, usually, motivated by one or more of the following circumstances:

- The existence of visible defects in the building;
- Damage after a particular event that affects its stability (earthquake, etc.);
- The change of the use of the building for most severe conditions; and
- Requirement of the competent authority, for instance, when there is an increase in the actions (earthquake action, traffic action, etc) imposed by new codes.

A basic point in considering structural rehabilitation of a heritage building is establishing the performance level to be fulfilled, particularly, the requirements in terms of structural safety, i.e., the structural safety level.

When there are no official documents, like standards or codes, to be used for the work, the required targets will be established, prior to the intervention, by agreement between the owner, the designer and the competent authority.

In particular circumstances, the performance level of the building can still be adjusted during the assessment phase, by agreement between those entities.

2.2 Criteria for intervention

Heritage buildings, by their very nature and history (material and assembly), present challenges in diagnosis, analysis and rehabilitation, which limits the application of modern legal codes and building standards.

Furthermore, the structural rehabilitation of heritage buildings has implications of architectural, structural, economic, historic and social order, depending on the degree and extension of the intervention. All these aspects will be taken into consideration.

The intervention for structural rehabilitation will involve the application of technical knowledge, and also, cultural sensitivity. Only when technique and culture are present, can the best decisions about the intervention be taken.

To succeed well, from the technical and the cultural points of view, intervention will be carried out on the basis of principles. The Venice Chart (1964), for example, which is one of the reference documents for the rehabilitation of architectural heritage, defends the adoption of the following principles:

- Guarantee of structural safety;
- Respect for the cultural value of the building;
- Minimum intervention;

- Reversibility of the intervention;

- Integration on the whole building;

- Compatibility of the materials;

- Minimum cost.

It is not always possible to follow all these principles at the same time, because, sometimes, they conflict with each other. For example, the achievement of structural safety conflicts, very often, with respect for the cultural value of the building. Another case is the reversibility of the repair of cracks in masonry elements, which to be adequately solved, will not be reversible.

In each specific case, compromises between those principles will be necessary, hopefully, subjected to common sense. Maybe, instead of principles, it will be more appropriate to consider them, simply, as references; i.e., reference terms for the interventions.

The Recommendations of ICOMOS, referred to above, also contain some Principles, where the basic concepts of conservation are presented, and Guidelines, where the rules and methodology that the designer will follow are discussed. Both those Principles and Guidelines will also be followed in this Guide.

2.3 Methodologies for intervention

The intervention for structural rehabilitation of heritage buildings comprises, in general, the following phases/actions:

- Acquisition of documented data about the building;

- Detailed survey of the existing condition of the building;

- Elaboration of the diagnosis (eventually, with the carrying of tests);

- Assessment of the structural safety;

- Design of the solutions for the intervention;

- Execution of the intervention.

A detailed description of these phases/actions will be presented on the following sections.

Depending on the actual conditions of the building and on the objectives to be fulfilled, the intervention can assume different forms, going from the non invasive (with the imposition or not of restrictions of use), passing through different kinds of works of repair and/or strengthening, until, eventually, partial demolition followed by reconstruction.

The decisions about the solutions to be adopted on the intervention will still be submitted to a cost-benefit analysis, in which all the relevant aspects will be considered, namely, the compatibility of the structural safety with respect to the cultural value of the building, and the cost to be as low as possible.

3 THE EXISTING INFORMATION ON THE BUILDING

3.1 Documented data about the building

3.1.1 The historical survey

Any intervention for structural rehabilitation of a heritage building needs information about its past, namely, about the concept of the building, as well as about the phenomena to which the building has been subjected.

This historical survey, covering the entire life of the building, aims at understanding the concept and the purpose of the building, the techniques used in its construction, the alterations made to it and its environment, as well as the events that could provoke damage to the structure, namely, its seismic history.

In the analysis of the documents about the past of the building, attention will be given to any references about degradation, reconstruction, additions, structural modifications, etc, or to any other event that can describe the actual situation of the building.

However, attention will also be given to the quality of the documents used. In fact, existing documents have, in general, been prepared for a purpose different from that of structural engineering, so they can include information incorrectly described, or omit important facts or events that can have influenced the structural behaviour of the building. The sources of information should be graded according to their value or the confidence that they inspire.

Data on the past and the present modes of use or occupancy of the building are aspects also important to be verified. The eventual action of significant environmental conditions, such as, climatic effects, sudden temperature changes, fire, or any accidental loads (impacts, etc.) will also be identified.

3.1.2 Survey of the construction of the building

The construction of the building, including its configuration, the types of structural components, and the materials used, are aspects that will need considerable attention.

This information will be obtained from the historical archive on the building, or from other sources, such as, reports, drawings, photos, etc, to which it will be possible to have access. It will be complemented with information to be obtained during the inspections to be carried out on the building, as well as, with interviews with persons familiar with the building.

Important points on this survey are the identification of the building materials and of main structural system of the building, as well as the detection of irregularities or weak points in the building that can have influenced its structural behaviour.

3.2 Survey of the defects in the building

The survey of the existing defects in the building is usually called preliminary inspection of the building. This survey will be carried out through visual inspection of the building, eventually, with the help of simple optical devices (binoculars, etc). In some cases the opening up of the surface of elements of the building, will be required.

In the case of high-rise buildings, or of elements with difficult access, this inspection can require the installation of appropriate means of access (scaffolding, cranes, etc.). The inspection of roofs can require particular safety measures.

The results of the preliminary inspection will be given in a report, in which the different materials and their degradations, as well as the damage to the structural elements, will be presented.

The defects observed will be classified qualitatively, according to their level of importance with respect to the safety of the building. The defects will be shown on adequate drawings (Fig. 1), or in the form of check-lists, appropriate to the different types of structural elements.

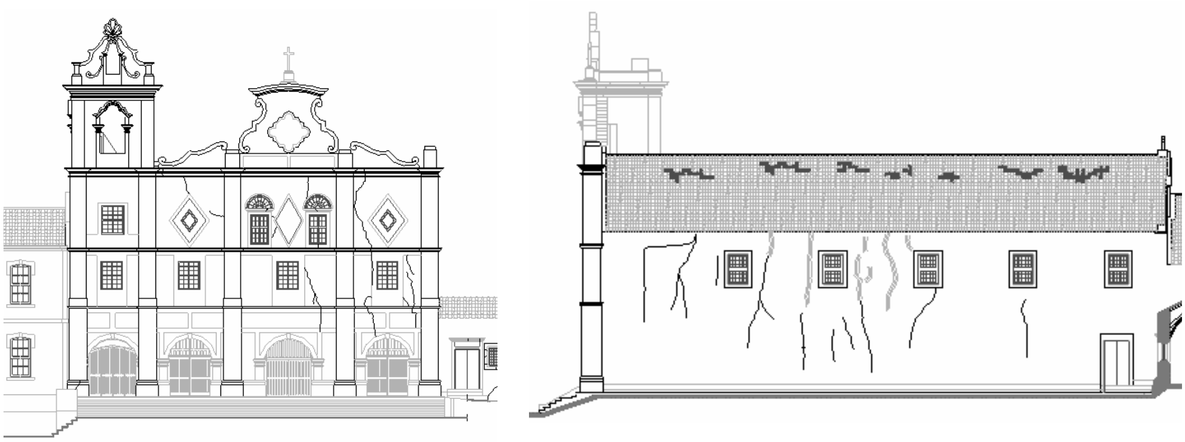


Figure 1: Mapping of the defects in a building (13)

The registers will be accompanied by detailed photo reports, which can allow for the relevance of details, which, sometimes, miss observation. A video register can also be used, which can allow for still more detailed information about the situation in the building.

In the preliminary inspection it will also be important to verify if the atmospheric agents are degrading the building in a particular way. In fact, those effects are often aggravated if adequate measures have not been taken during construction (adequate drainage, for example), or, if there has not been efficient conservation of the building.

It will still be important to obtain information about the geotechnical conditions of the soil supporting the foundations of the building, namely the existence of embankments. If there are degradations in the lower part of the building, it will be convenient to get samples of the soil, in order to verify if there is contamination by aggressive substances (sulphates, etc.).

3.3 Preliminary assessment

After the preliminary inspection, and taking into account the documented information, a preliminary assessment of the situation in the building will be carried out. This preliminary assessment aims to decide about the need to continue (or not) the investigations and about the eventual need for urgent measures to be undertaken, related, namely, to the continuation of the use of the building, or to the installation of temporary supports.

If the available information will not be sufficient to elaborate the diagnosis of the situation in the building, the preliminary assessment should be complemented by a detailed assessment, through the carrying out of tests and measurements on the building (detailed inspection). These measurements can also include the geometric survey of the constitution of the building, in order to its modelling, as it will be referred later.

3.4 Defects in the building

3.4.1 General

The defects in the building can result from the degradation of the building materials or from the damage of the building elements due to mechanical actions.

The degradation of the building materials is a process that develops naturally with time, and can be accelerated by chemical, physical or biological actions. The main effects are the deterioration of the surfaces of the elements, the loss of material and the reduction of their strength.

The phenomena of degradation are different according to the type of building material: masonry, timber or steel (iron).

The damage to the building elements due to mechanical actions occurs when the actions in certain zones of the building element exceed the strength of their materials. They can be produced, or be aggravated by actions, or by insufficient strength. Alterations on the constitution of the building can also be the source of damage of this type.

The manifestation of damage to building elements due to mechanical actions will depend on the type of action, the type of building material and the type of building element.

3.4.2 Degradation of building materials

a) Masonry

The degradation of masonry is linked to the characteristics of the constituent materials: bricks, blocks (of stone or concrete), and mortar filling the joints. It will be necessary to correctly identify the materials: the stone (limestone, sandstone, etc.), the bricks (fired or sun dried, etc.), and the type of mortar (cement, lime, etc.).

Masonry is affected by the presence of water (rain, moisture, etc.), temperature variations (freeze/thaw cycles, etc.) and microclimatic conditions (pollution, etc.), which can provoke its weakness through the development of micro-cracks, with the consequent loss of material, particularly if the masonry is not protected by rendering (Fig. 2a). The excessive dryness, as well as, wind, also can weaken masonry.

Degradation of masonry due to the presence of salts (sulphates, nitrates, etc.), in the case of brick masonry, and to biological colonisation (moss, etc.) in the case of stone masonry, can also be very significant (Fig. 2b). The excrement of birds (pigeons, etc.) is, usually, the greatest source of these types of problems.

A very important problem with masonry is the action of water resulting from the rupture of pipes embedded in walls, which can quickly cause damage.

a) Loss of material in columns (14)

b) Biological colonisation (14)

Figure 2: Degradations in stone masonry

b) Timber

The main causes of the degradation of timber are the attack by fungus and insects. Timber species are variably susceptible to degradation and attack, so, a very important issue is the correct identification of the specie of the timber element.

The favourable conditions for the development of fungus in timber are water content higher than about 20% and high temperatures (25 to 35ºC). The insects xylophages (worms, etc.) develop in drier environments.

Timber elements of roofs, particularly in the vicinity of their supports, are the most susceptible to fungus attack, due to the presence of rain water (Fig. 3a). The support zones of timber floors on masonry walls are also, often, a source of moisture, due to the infiltration of water through the walls (Fig. 3b).

a) In roof elements (21)

b) In floor elements (27)

Figure 3: Degradations in timber

Attention has also to be given to situations in which the timber is integrated in masonry, as are the cases of walls reinforced with timber trusses or wooden partitions.

Particularly delicate are the situations in which there are alternate dry/moist conditions, as is the case of timber piles enclosed in soil having a variable water table; this can lead to the quick rotting of the timber.

The presence of cracks in timber elements, parallel to the fibres, due to the shrinkage of the timber, generally is not a problem, except in the case of very thick elements, when a significant reduction of the shear resistance can occur.

c) Steel (iron)

The greatest problem with steel and iron elements is corrosion, in particular, of the connections by rivets or bolts.

Another important problem to be taken into consideration is the eventual corrosion of the steel elements embedded in masonry elements, which can lead to the rupture of those elements, due to the increase of volume resulting from the rust.

It is also to be noted that the iron or steel of old buildings are, in general, less ductile and less resistant to fatigue than the iron or steel produced nowadays.

3.4.3 Damage to building elements

a) Walls and columns

The relevant actions for the damage to walls and columns are, in general, the vertical loads: self-weights, weights of the floors, etc. Lateral actions, namely the thrust of arches and earth pressure, and, particularly, the effects of earthquakes are also, sometimes, very relevant.

In the case of masonry elements, due to their low tensile strength, vertical loads can cause vertical cracks, which can lead to the development of lateral deformations and to the detachment of material. In the case of composite walls, with two exterior leaves and an interior in-fill, separation of the exterior leaves from the interior in-fill can also occur.

This kind of damage can develop slowly (over centuries), or rapidly, but, once the process starts, it can lead to the collapse by crushing of the structural element, even if the actions do not increase. The creep of masonry (not recognised in the past), can aggravate cracking and lead to collapse, even when stresses are moderate.

If the vertical loads are eccentric they can cause rotation of the element around the base, with the development of vertical cracks and the crushing of the material on the most compressed zone. Concentrated loads of high magnitude can also lead to the localized crushing of the building element.

Lateral actions in masonry walls can cause diagonal cracks (Fig. 4) or disruption between elements (Fig. 5), due to the low tensile strength of the units and of the joints. In masonry columns, lateral actions can also lead to their loss of stability, overturning, or to horizontal displacements on the joints between blocks (Fig. 6).

Figure 4: Damage in walls due to earthquakes (40)

b) Arches, vaults and domes

In arches, vaults or domes in masonry the main source of problems is the movement at the supports, with the development of tension, and, as a consequence, the opening of cracks. Such movements are related to the occurrence of the following conditions:

Figure 5: Damage in walls due to earth pressure (21)

Figure 6: Damage in column due to earthquakes (21)

- Deficient conception or execution of the element: inadequate geometry for the distribution of loads; insufficient resistance or stiffness of tie-rods and buttresses; poor quality of the constituent materials, etc;

- Alteration of the distribution of loads (sometimes, loads are taken off or added in certain zones of the element, particularly, fillings);
- Actions not foreseen: differential settlements of the supports (Fig. 7), etc;
- Inadequate maintenance: degradation of the constituent materials, weakness of tie-rods and buttresses, etc.

Masonry vaults supported by steel beams in building floors are particularly sensitive to lateral movements of the supports, due to their, usually, low rise.

Figure 7: Cracks in a masonry vault (24)

c) Towers and chimneys

These types of elements are characterized by being, in general, subjected to high compression stresses in the bottom zone, which can lead to the development of vertical cracks, as referred to for walls (Fig. 8).

They are particularly sensitive to movements of the foundations and to alterations, namely to the introduction of openings. Prismatic elements can also be weakened by imperfect connections between walls.

Figure 8: Vertical cracking in a masonry chimney (21)

d) Framed elements

The main problems encountered with framed elements of timber or steel, used as the structure of the roofs or floors of buildings, are the deformation of the elements or of the joints, due to excessive loads or to actions not took into account in the design, such as earthquakes, for example.

3.5 Detailed assessment

3.5.1 General

As referred to above, when the available information is not sufficient to elaborate the diagnosis of the situation in the building, the preliminary assessment will be complemented by a detailed assessment of the building. This detailed assessment will include a detailed inspection, which can comprise in-situ tests, laboratory tests, field tests, assessment of the foundations and also field measurements.

As tests are, in general, very expensive, and carrying them out can affect the cultural value of the building, the number and the place in which they are planned to be performed should be considered sensitively. As a rule, the tests to be carried out will be based on a clear vision of the phenomena for which characterization or understanding is relevant.

In the planning of the program of tests, two phases will, in general, be considered: the first one, in which the aim is the acquisition of the primary information; and the second one, in which the aim is to refine the information obtained during the first phase, carrying out an additional number of tests or more specific tests.

After carrying out the tests, the results obtained will be carefully analysed. In particular situations, alternate methods of tests will be used, and their results compared, for calibration.

The tests can be non-destructive (or slightly intrusive), when they have a negligible influence on the building, or destructive (in any way), otherwise.

Non-destructive tests ("NDT") are, obviously, the preferable ones for heritage buildings. If non-destructive tests will not be sufficient, destructive tests will be considered, but they will be carried out only after a cost-benefit analysis.

In this analysis, the global cost will be the cost of the tests plus the eventual loss on the cultural value of the building due to the carrying of the tests, and the benefit will be the eventual reduction on the size of the intervention due to the improvement in the quality of the information.

3.5.2 In-situ tests

In the case of masonry elements, the available most common non-destructive techniques for in-situ tests are ultra-sonic tests and analysis with endoscope; flat jack tests are also very useful, but they are slightly destructive.

The ultra-sonic device measures the speed of a sonic pulse through the masonry element. It allows for information to be obtained about the stiffness and the resistance of the masonry, but in a qualitative way, only. It also allows for information about the presence of voids or other discontinuities. It is completely non-destructive.

The endoscope (fibre optic viewing device) allows the observation of the interior of masonry elements and the conditions of the materials around holes drilled in those elements. It is very effective, causing minor damage for a moderate cost.

The flat jack technique consists of the formation of small slots in the masonry, in which flat jacks of small depth are introduced (Fig. 9).

By measuring the applied pressures, as well as the deformations between the slots, this technique allows the measurement of the stress-strain relationships of the masonry between the slots, and so the obtaining of its modulus of elasticity.

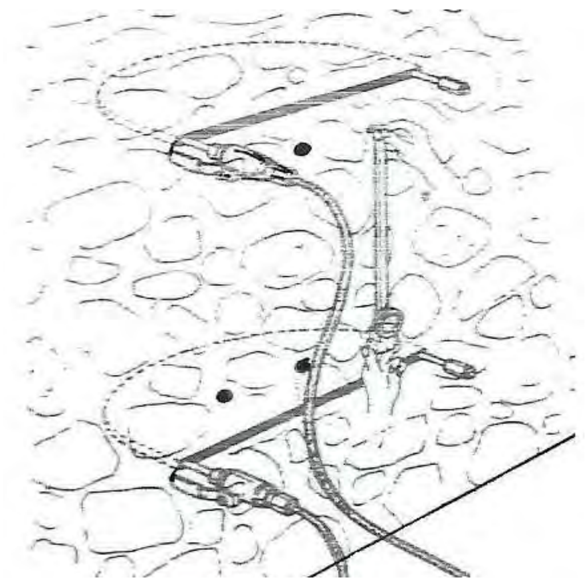


Figure 9: Tests with flat jacks in masonry walls (2)

Increasing the applied loads, this technique can also enable the resistance of the masonry, in compression, to be obtained, but, in that case, it becomes partially destructive. Jacks need to be calibrated individually.

In the case of thick walls, instead of flat jacks, one can use the dilatometer, (whose principle of functioning is identical to that of flat jacks), which is introduced along holes made through the walls (as in the case of the endoscope).

Other techniques, also useful, are the drilling energy test and radar.

The drilling energy test, which measures the power consumption for drilling a standard diameter hole in masonry elements, has been used to assess their compressive strength. However, test results have to be calibrated by comparison with other means.

Radar measures the time of flight of radar pulses between the surface and reflecting features inside the masonry. It allows for the detection of ties inside the masonry, and also for measurement of thicknesses in masonry elements. It is also useful to detect zones with moisture, voids, or other discontinuities, as an alternative to ultra-sonic tests. It is completely non-destructive.

In the case of timber elements, in-situ non-destructive tests are also available, such as, the use of the metallic blade and the impact hammer. They are not very reliable, yet, so they will not be used in isolation.

In the case of steel elements, the most common in-situ test is the impact hammer, which can allow information to be obtained about the extension and the depth of corrosion.

3.5.3 Laboratory tests

The assessment of the characteristics of building materials is usually carried out taking samples from some of the structural elements: cores, in the case of masonry elements, and small fragments, in the case of timber or steel elements, and carrying out laboratory tests on specimens made from those samples.

The laboratory tests can be mechanical tests: of compression, tensile or of shear strength, etc. (Figs. 10a and 10b); chemical tests: chemical composition, etc.; or mineralogical tests: mineralogical composition, etc.

a) Masonry core (21)

b) Steel specimens (21)

Figure 10: Specimens for material testing

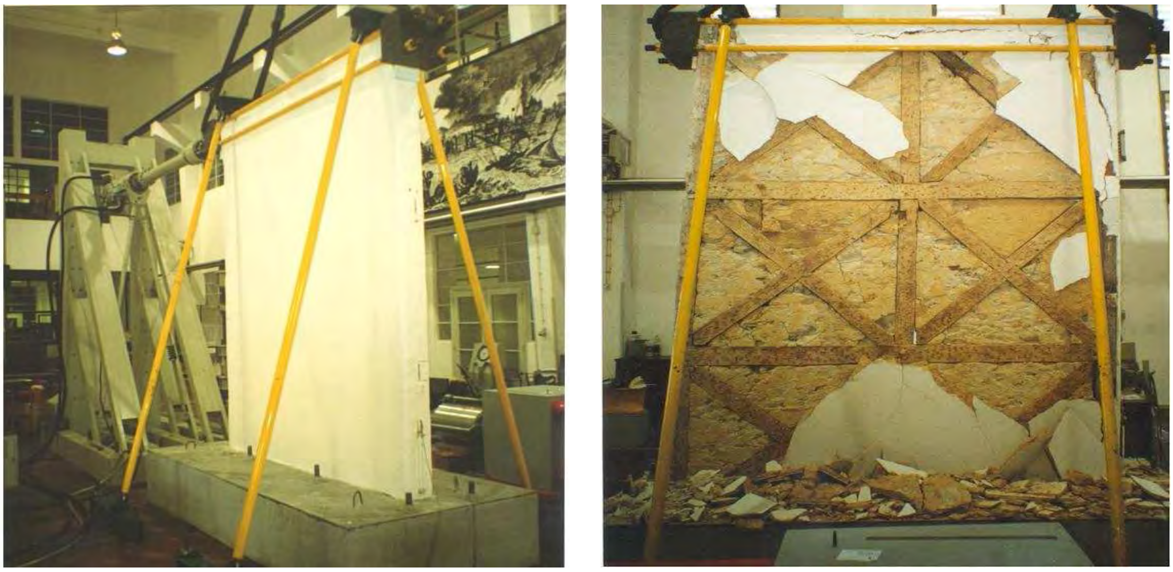
The taking of samples from the building will be carefully specified as to their number and their location in the building, in order that the information obtained has the required quality and that the cultural value of the building will not be significantly affected. It will be verified that the taking of the samples will not compromise the existing structural safety of the building, particularly, in the case of steel or timber elements.

Figure 11: Specimen of masonry wall for a shear test in laboratory (21)

In the case of very thick masonry walls, attention will be given to the fact that they can be very heterogeneous, having, in general two exterior leaves of good quality, and an interior core, generally, of rubble of bad quality. To take into account this heterogeneity, large samples (prisms) have to be taken from the site and tested after adequate preparation in the laboratory (Fig. 11). As this solution is very much intrusive and expensive, it can only be adopted in particular circumstances, for example, when demolition is to be carried out.

Sometimes, even complete walls are taken from the site and tested in a laboratory, allowing for obtaining, with great accuracy, the mechanical characteristics of masonry in compression and in shear, as well as the evaluation of the seismic behaviour of the building (Fig. 12).

When it is not possible to take samples from the masonry in the building, one alternative solution consists in building specimens in a laboratory, using units and mortar identical to the original ones. Apart from the difficulty in building specimens that simulate the real walls this solution has the advantage of enabling them to be made in great numbers, allowing also for the simulation of the variation of several parameters.

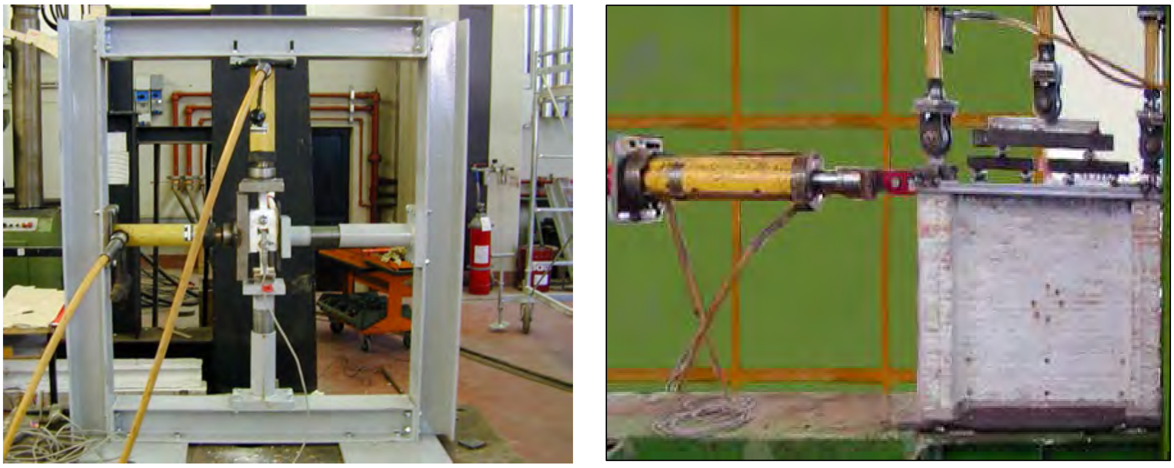


a) Test set-up

b) The wall after tested

Figure 12: Laboratory test of a timber framed infill wall under cyclic alternated actions (5)

Instead of macro-specimens, it is also possible to carry out tests in a laboratory using micro-specimens (Figs. 13), taking into account the scale effect, when relevant (Fig.14).



a) Triplet test

b) Shear test

Figure 13: Apparatus for shear tests on masonry specimens at 1/3 scale (40)

It is to be noted that the empirical models adopted in modern codes, which use relationships between the compressive strength of the masonry, the masonry units and of the mortar, are, in general, not applicable to old masonry.

3.5.4 Field tests

Characterisation of the strength of the masonry in compression or in shear is sometimes carried out, using testing devices appropriate to the field conditions (Fig. 15). Since these tests become very intrusive to the building, they are only possible in very particular situations.

Figure 14: Shaking-table test of a masonry building at 2/3 scale (41)

Figure 15: In-situ test of the lateral resistance of a masonry wall (26)

To characterize the dynamic behaviour of the building, dynamic tests are often used, allowing for obtaining the fundamental frequencies, damping, etc., which will be very useful, particularly in the cases of complex masonry buildings. The comparison of the results obtained on these measurements with those obtained from the modelling of the building, will be very helpful for the refinement of the structural model of the building.

3.5.5 Assessment of the foundations

The knowledge about the existing foundations of the building will be of primary importance. Besides the geotechnical characterisation, it will also be necessary to conduct research to allow for the definition of the geometry of the foundation elements.

The assessment of the conditions of the foundations is usually made through the execution of shafts in particular zones of the building (Fig. 16).

In this assessment attention will be given to the characteristics of the soil and to the water table, as well as to the presence of substances that can attack the building by capillary action (chlorides, nitrates, etc.).

Figure16: Shaft for the geotechnical recognition of building foundations (21)

Particular attention will also be given to check the existence of embankments and to the identification of the drainage system of the building.

The adequate characterisation of the foundation soil sometimes needs undisturbed samples to be taken and tested in the laboratory. Penetrometer tests are also of great value, allowing for the stratification to be assessed and for a reduction in the number of samples needed.

3.5.6 Field measurements

The detailed assessment of a building can also include the measurement of deformations in structural elements of the building, such as the inclination of columns and the lateral deformation of walls. Sometimes, it includes, simply, the measurement of the width of cracks in building elements (Fig.17).

It can still include the detailed survey of the geometry of the building, in order to allow for its modelling, so as to support the diagnosis, and for the structural assessment of the building.

Figure 17: Ruler measuring the width of cracks in walls (21)

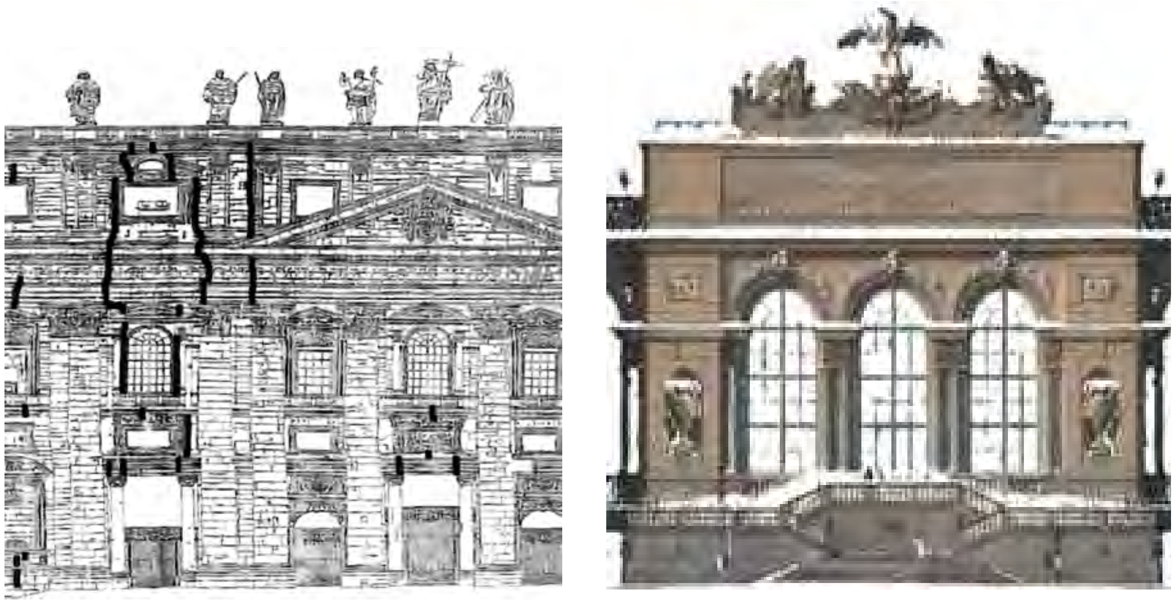
The measurement of deformations in structural elements of the building usually uses topographic techniques, such as precision levelling, etc.

In the measuring of the dimensions of the building elements, the topographic techniques are also used, in addition to the common means of measuring dimensions in the field. Usually, advantage is taken of the installation of any special means used for the visual inspection, to carry out this survey.

For the measurement of the thickness of the elements a method commonly used is radar. However, as this technique is not very accurate, it has to be complemented by other means, for example, with the drilling of small holes through some elements, for calibration.

In the case of monuments or other complex structures, the photogrammetric technique can also be very useful for the survey of the geometry of the building, as well as for the register of the defects in the building (Fig. 18a).

More recently, the "laser" sweeping technique has appeared, which allows for the obtaining of a "cloud" of coordinated points in "3D", from which it is even possible to construct a numerical model of the building (Fig. 18b).



a) Photogrammetric survey (16) b) Laser sweeping survey (21)

Figure18: Survey of the geometry of the building

3.6 Monitoring of the building

The monitoring of the building during a certain period of time can be an adequate measure to help the elaboration of the diagnosis, particularly when there may be non-stabilized phenomena, allowing for showing its evolution.

The monitoring of the building consists in the measurement of parameters, such as, deformations, movements of cracks, levels, temperature variations, etc., in strategic points of the building, at certain moments, during a certain period of time.

The monitoring techniques can range from the simple placing of gypsum 'tell-tales' (Fig. 19a) or crackmeters on cracks, to a modern monitoring systems using sensors: electric extensometers, displacement transducers, thermometers, accelerometers, etc. (Fig. 19b), connected to a data acquisition device, which can acquire data at pre-defined intervals of time. The photogrammetric technique can also be used as a method of monitoring.

The monitoring of the building can also be done during the rehabilitation phase, in which the data that is being obtained is used as a basis for subsequent decisions, allowing, sometimes, for the reduction of the size of the intervention. Continuing monitoring of the building can also be useful after the rehabilitation works, or when doubts still remain about the need for more measures of intervention (long-term monitoring).

By comparing of the results obtained from the monitoring of the building with the results obtained from its modelling, it will be also possible to refine the modelling (see section 4).

Monitoring systems permit the storage of the acquired data and its transmission via land lines or through the internet. They can also function as an alarm, which can be very useful in some situations.

a) With gypsum 'tell-tales' (21) b) With displacement transducers (3)

Figure 19: Monitoring of cracks in buildings

Because the installation of a monitoring system in the building is, in general, very expensive, it should be the object of a cost-benefit analysis and only the information relevant to the evolution of the phenomena will be registered. The subsequent treatment of the information that is being acquired should also be assured.

3.7 Elaboration of the diagnosis

The diagnosis of the situation in the building is the process of identifying or determining the nature and the cause of the defects in the building.

The diagnosis is a very delicate task, because the available data refers to the effects (symptoms), while the causes that are their origin (or, as it usually happens, the several concomitant causes) are what need to be identified. Intuition and experience are essential components of the diagnosis.

On figure 20 a flowchart of the actions to be undertaken in the elaboration of the diagnosis is presented.

For the elaboration of the diagnosis, an interpretative model (scenario) that interprets the existing defects in the building will be established, based on the results of preliminary inspection. When that information is not sufficient, it has to be complemented by a detailed inspection, and, eventually, by the modelling of the building.

On this modelling, usually, simplified models are used, but, in some circumstances, sophisticated models may be needed (see, section 4). The properties of the building materials and the values of the actions to be adopted on this modelling will be the nominal ones, obtained directly from the tests or from the field measurements, without using any safety coefficients).

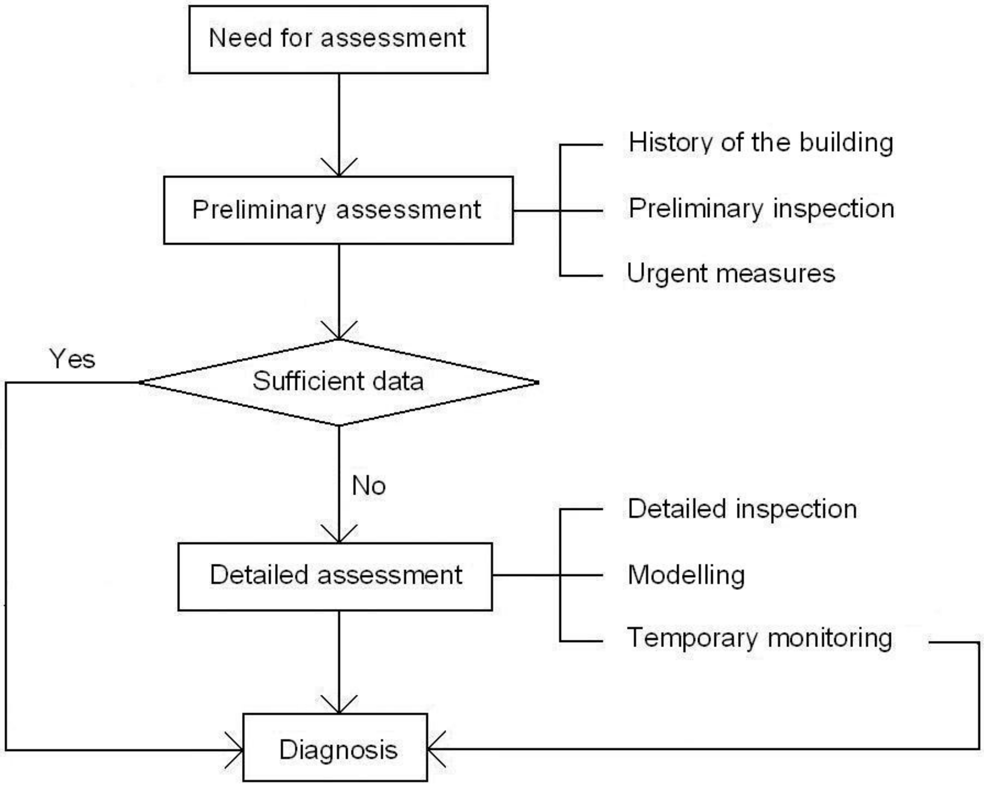


Figure 20: Flowchart of the actions to be undertaken for the diagnosis of the building (38)

These sources of information will confirm (or not) the interpretative model (scenario) that has been advanced. In the last case, an alternate scenario will be established and, eventually, confirmed.

If the situation does not become completely clear, the best solution will be to keep the building under observation (monitoring) for a certain period of time, which will allow for the evolution of the phenomena and, subsequently, for a better understanding of what is, in fact, happening to the building.

4 STRUCTURAL ASSESSMENT OF THE BUILDING

4.1 Introduction

The structural assessment of heritage buildings is the evaluation of the collected data related to the safety of the building, with the objective of deciding whether its structural safety is sufficient, or not. It is an essential phase of an intervention of rehabilitation, because it is when it is decided if measures are necessary and to what extent.

The structural assessment of the building is usually based on the modelling of its structural behaviour, in which, as for new buildings, through certain hypotheses, the effects of the actions on the building are determined and combined, being the results compared with the strength of the building (or in strategic points of the building).

However, due to the specifics of heritage buildings there are substantial differences in the procedures to be used on both the structural modelling and on the safety verification, in comparison with new buildings.

Concerning the modelling of the building, it is to be noted that, owing to the simplifications that are, in general, necessarily adopted, and to the possible lack of knowledge about the events to which the building has been subjected in the past, the results obtained are, in general, less reliable than would be the case for the design of new buildings.

Concerning the safety verification, specific issues also arise. In modern codes, the uncertainties, both on the side of the strength of materials and on the side of the actions, are taken into account through the application of successive safety coefficients, which lead in practice, to a high safety level on the buildings.

This approach is, generally, well accepted by society, because the increase in safety does not result in a significant increase of cost. In the case of heritage buildings this approach would be inappropriate, because it could require very intrusive and costly rehabilitation works, which, sometimes, are not justified. Furthermore, as the properties of the building materials naturally decrease with time, safety levels lower than those in new buildings would be acceptable for existing buildings.

It is also to be noted that the safety coefficients prescribed in the design of new buildings take into account uncertainties related to the building process, which, in the case of existing buildings do not exist, because their behaviour can be observed. The possible reduction of these coefficients does not mean, necessarily, that the safety of the building is not acceptable.

4.2 Safety level of the building

In establishing the required safety level of heritage buildings, a holistic and flexible approach should be adopted, in a way that, to guarantee their safety, the strengthening measures to be carried out will be reduced as much as possible, and the loss of the cultural value of the building will be minimized.

Thus, in heritage buildings, safety levels lower than those prescribed for new buildings will be acceptable, since it will be possible to take measures in order to reduce the risk associated with diminishing the safety level, for example, by adopting restrictions on the use of the building.

Furthermore, in the case that safety levels identical to those prescribed for new buildings are adopted, partial factors for both the strength of the materials and the values of the actions, lower than those prescribed for new buildings, can still be used if the assumed reduction of the uncertainties associated with these variables is taken into account.

The establishment of the safety level of a heritage building should, in particular cases, be subjected to a cost-benefit analysis, being the benefit the reduction of the risk, and the cost being the possible reduction of the cultural value of the building resulting from the intervention of rehabilitation, in addition to the cost of the intervention itself.

As referred to above, in the case of buildings with high cultural value the safety level to be adopted should always be agreed between the designer, the owner and the competent authority.

4.3 Modelling of the building

The structural model (or models) of the building are the set of structural elements (components) used to represent the structural functioning of the building. The model should adequately represent the structural behaviour of the building and the phenomena which are related to it, using calculation methods that are readily available, as much as possible.

The process of modelling of heritage buildings is similar to that for new buildings, in which, information about the existing stresses (or ones that can be produced) in the various structural elements of the building are calculated.

As referred to above, the modelling of heritage buildings is, in general, more difficult and less reliable than in the case of new buildings. This is due to several factors, such as:

- The difficulty in adequately modelling its structure;
- The uncertainties related to the characteristics of the constituent materials in the whole building;
- The influence of past phenomena or events (not always obvious), as well as, the imperfect knowledge about alterations or repairs made in the past.

Apart from the lower reliability, the data obtained from the modelling of heritage buildings will be always useful, giving, at least, trends, such as the direction and order of magnitude of the stresses, possible critical zones, etc. The modelling will also be helpful in the design of the eventual strengthening, by comparing the results obtained with the modelling of the existing building with the results obtained for the same building on which the strengthening measures that are being planned, are included.

For the modelling of heritage buildings, models with different levels of sophistication can be used, depending on the specific situation.

In some situations, and for a preliminary evaluation, simplified models, based on simple static conditions of equilibrium, manual calculations or graphical methods (Fig. 21) can be useful.

However, nowadays, the most common modelling methods are the numerical ones, using meshes of finite elements, appropriate for the representation of the behaviour of the structural elements of the building.

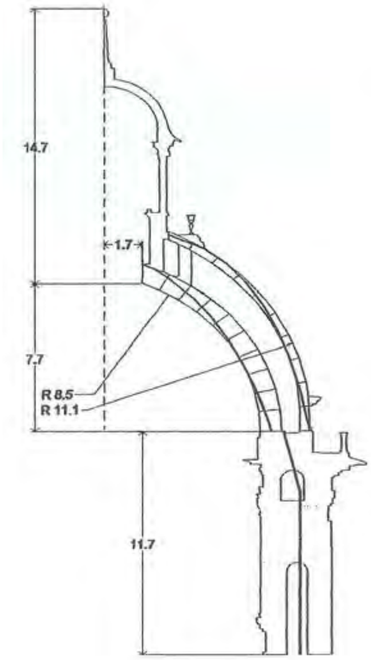


Figure 21: Modelling of masonry dome through the funicular of loads (4)

There are several computational software methods, commercially available for the modelling of heritage buildings, both static and dynamic, with varied sophistication.

For common buildings, the simple planar (or three-dimensional) multi degree of freedom shear systems are currently used. For buildings such as monuments, churches, etc, it will be more appropriate to use software with finite continuum elements (Figs. 22 and 23).

It is to be noted that the analysis through complex models is, in general, expensive, because of the preparation of the input data and of the consideration of the quantity of results obtained. Furthermore, it requires great experience and intuition about the structural behaviour of building structures.

The setting up of the structural model of the building will be based on the survey of the building and of its environment. When available, the existing information about the building, such as memories, drawings, photos, etc., can be used, but they should be confirmed, at least, partially.

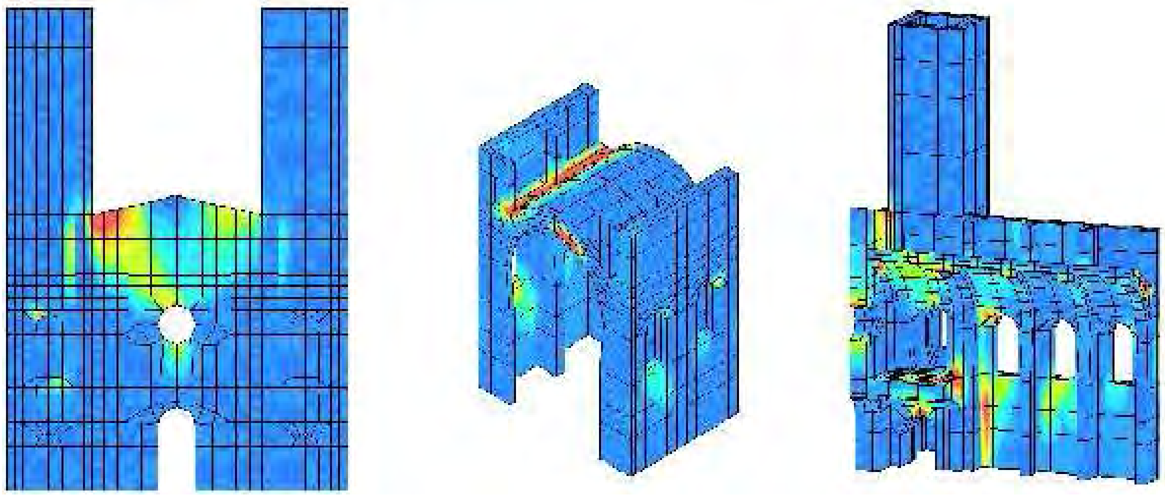


Figure 22: Computational models for the structural analysis of complex building (13)

In the case of buildings which are significantly cracked, it will be convenient to use models that can simulate the cracking.

When non-linear models are used, the constituent relationships of the elements should be based on the results obtained from the mechanical tests carried out for the characterization of the building materials, even if much information about heritage materials is currently available.

Another important aspect is the alterations suffered by the building over time, which can lead to a significant change in the stress distribution, such as stresses resulting from the construction of openings, the development of unbalanced forces due to the removal of components (arches, walls, etc.), the increase of weight due to increase in the height of the building, the reduction of the capacity of the soil due to the execution of excavations for neighbouring buildings, etc.

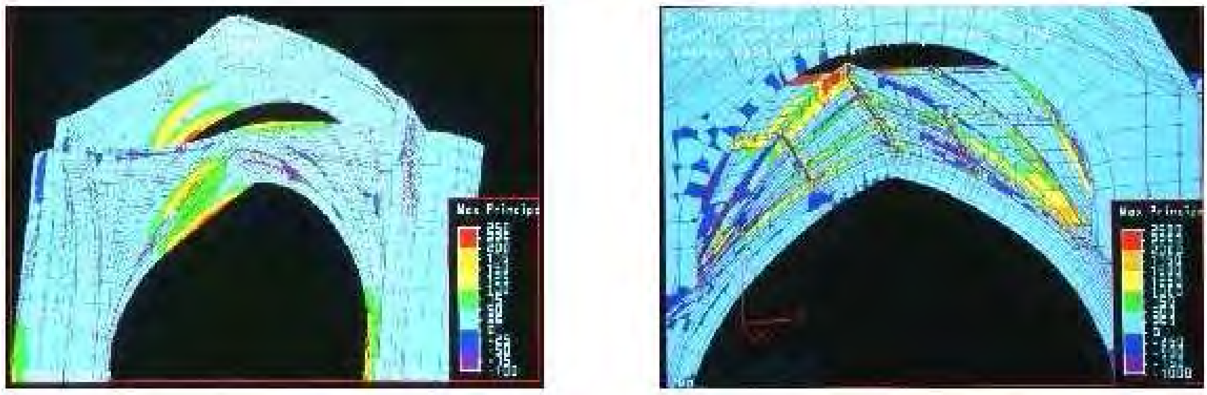


Figure 23: Modelling of a masonry vault before and after strengthening (8)

In the case of very heavy buildings it will be also convenient to take into account the assumed sequence of loading during construction.

In the case of very complex buildings it will be convenient to use alternative or complementary models, starting from simple models and increasing the refinement of the analysis taking into consideration the results that are being obtained. It is to be noted, however, that, with different models, substantially different results can be obtained in the same structural element.

In the case there is information about the dynamic characteristics (fundamental frequencies, damping, etc.), obtained from in-situ tests carried out on the building, they should be compared with those obtained through the modelling of the building, which will allow for their calibration and for the refinement of the modelling.

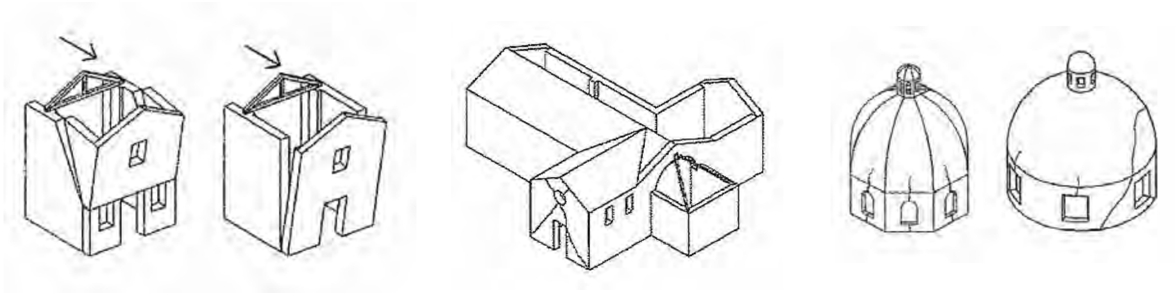
For the seismic evaluation, the following modelling methods can be used: static linear analysis; dynamic modal (linear) analysis; nonlinear static (pushover) analysis; and, non linear dynamic analysis.

In the case of common buildings composed of a system of external and interior bearing walls, placed in various directions, and a system of intermediate diaphragms, efficiently connected to the walls in order to guaranty the so called “box-effect”, three-dimensional multi-degree of freedom shear systems, with masses concentrated at floor levels, will be adequate.

In this case, calculations can still be simplified by taking into account only one horizontal component of the seismic ground motion and analyzing the structure in each orthogonal direction, separately. Linear static analysis will usually be performed, being the results corrected by the behaviour factor.

In the case of buildings with large halls and without intermediate diaphragms, like churches, or when the diaphragms are not completely efficient, in which the collapse is mostly caused by the loss of equilibrium in limited portions of the building, it will be more adequate to use the macro-modelling.

In macro-modelling, the building is divided into structural components, the macro-elements, characterised by a substantial autonomous structural response (facades, halls, domes, etc.), to which linear or nonlinear static analysis will be conducted (Fig. 24). On each macro-element one or more collapse mechanisms (usually, out-of-plane damage and collapse mechanisms), will be identified and their vulnerability quantified.



a) Overturning of facades   b) Shear mechanisms in walls   c) Domes

Figure 24: Macro-models and collapse mechanisms in different heritage buildings (36)

In the case of flexible buildings, like towers and bell towers, in which the influence of the higher modes may be important, the dynamic modal analysis can be more adequate. However, the behaviour factors will be more difficult to establish, and they will depend, mainly, on the quality of the clamping between the walls and on the possible contact with other buildings.

Nonlinear static (pushover) analysis is a non-linear static analysis under constant gravity loads and monotonically increasing horizontal loads. It will be appropriate for complex buildings, using models that represent the global behaviour of the building and its resistance deterioration (softening), in which the acting forces are considered proportional to the masses, or distributed linearly, or according to the first mode.

Nonlinear dynamic analysis should be used in particular cases, only, when the complexity of the building and the contribution of different modes of vibration do not allow the assigning of a seismic response to a single degree of freedom.

4.4 Quantification of the strengths of the materials

4.4.1 Mechanical properties of the materials

The mechanical properties of the building materials to be adopted in the modelling of the building will be, in principle, obtained from the results of appropriate tests, as it has been described in section 3. In the absence of test results, strengths can be established from comparison with other buildings or even from data-bases, but, in those cases, conservative values should be used.

When tests are carried out, the number will be, in general, very limited, so identification tests of the conditions of the building materials at strategic points of the building should be carried out. Identification tests will also be necessary when the mechanical properties of the building materials are estimated from comparison with other buildings.

It is to be noted that the mechanical properties of the materials, particularly the strength, are subject to degradation with time, due to chemical, physical or biological actions, and, thus, they can vary from point to point of the building. This degradation can be manifested at the surface, so that it becomes apparent during the visual inspection (cracks, erosion, etc.), but, sometimes, deterioration can only be detected through careful inspections, as is the case of damage in walls covered with rendering, or the attack of termites in timber elements, for example.

In respect of strength, the values to be considered for the building materials will be the characteristic values. They can be established at local level, for parts of the building, or, globally, for the entire building. Normal distributions are, in general, assumed, being the characteristic value obtained from the mean value and the coefficient of variation, taking into account the size of the sample. As the number of specimens is, in general, very low, simplifications are adopted.

In general, the characteristic value of the strength of the building material, f_k, will be considered the minimum of two values: the minimum value of the sample, f_{min}, or the mean value of the sample, f_{mean}, divided by 1.2. The sample should contain, at least, two values.

The design values will be obtained from the characteristic values modifying them by partial factors, called confidence factors. The confidence factors are related to the uncertainties associated with the determination of those characteristic values, thus, they will depend on the quality and the extent of the information. The confidence factors will also take into consideration the reliability of the geometric survey of the building.

4.4.2 Confidence factors

In codes for new buildings, the uncertainties associated with the determination of the strength of the building materials are, in general, established as a function of the category of execution surveillance and of manufacturing control. Therefore, usually, high values for those coefficients are prescribed, which, if applied on the assessment of heritage buildings, could lead to intense strengthening measures.

Because on existing buildings, the building materials are known, the partial factors for materials should be replaced by confidence factors, C_F , which will reflect the knowledge level of the actual material properties and of the geometry of the constructive elements of the building.

The value of the confidence factor for each material will be related to the number of samples tested and to the size of the building.

For masonry, the following C_F values will be used as reference values:

C_F = 1.1, when the mechanical properties are determined either by in-situ tests or by laboratory tests of specimens taken from the building, being the composition of the masonry verified by removing plaster at least in one location in each story of the building;

C_F = 1.35, when the mechanical properties are obtained by testing specimens in the cluster of buildings of the same type, and identification of the type of masonry is carried out by removing plaster and opening the walls at least in one location in each story of the building.

For intermediate situations of knowledge, intermediate C_F values will be established using those values as reference.

In a similar way, C_F values of 1.1 and 1.3, for timber, and of 1.0 and 1.1, for steel, respectively, will be used as reference values.

For the modulus of elasticity, *E*, and the shear modulus, *G*, of the masonry, the mean values obtained in in-situ or in laboratory tests, when existing, will be used as reference values.

4.5 Quantification of the acting actions

4.5.1 General

The actions that can arise on heritage buildings are the mechanical ones (forces, deformations, etc.) that produce stresses and deformations on the structural elements of the building, or the phenomena of chemical, physical or biological nature that can affect the material properties.

Concerning the effects of these phenomena, they are, in general, taken into account through appropriate reductions in the values of the strengths of the affected materials.

The values of the permanent loads (self-weights, etc.) will be obtained, in principle, from the survey of the geometry and of the construction of the building. Existing information, such as drawings, photos, etc, can also be used, but they should be verified, at least, partially.

Concerning the variable actions, the values prescribed in codes for new structures will, in principle, be adopted. In the case of the seismic action, however, lower values can be used.

Concerning safety against fire, it will be treated, in principle, in the same way as that in the design of new structures. In case it will doubtful, the best solution will be the adoption of protecting measures of the structural elements, instead of their strengthening.

4.5.2 Seismic action

Earthquakes are the actions that usually provoke devastating effects on heritage buildings, not only due to the intensity of the action, but also, because, in general, it has not been considered when the building was built. Those effects will depend on the location of the building, on the characteristics of the soil of foundation, and on the characteristics of the building itself.

However, many heritage buildings have resisted earthquakes with limited damage only, even when their resistance, calculated on the basis of experimentally obtained mechanical properties of masonry, has not completely met code requirements.

This finding allows for the ground acceleration values be reduced (i.e., higher probability of being exceeded is admitted) if the remaining life, the category of building and its use, and the effective seismicity level of the place, are taken into consideration.

Firstly, the reference seismic action should be based on the effective conditions of the site, avoiding the rigid way of subdividing into seismic zones, eventually, carrying out the micro-zoning of the site. Further, the reference level of seismic protection should be chosen on the basis of the importance of the building and of the conditions of use.

As a reference, a reduction factor γ_{1n} = 0.7 can be used in high seismic intensity zones (a_g= 0.30g), but no reduction, i.e. γ_{1n} = 1.0, will be used in low intensity zones (a_g= 0.10g). For intermediate situations, intermediate values can be established, taking those values as reference.

Considering the importance the building and its conditions of use, the seismic action can still be reduced, multiplying the values obtained above by a γ_2 factor which takes the value of 0.7 for buildings of low/medium importance and scarcely used, and of 1.0 for buildings of high importance and frequently used. For intermediate situations, intermediate values will also be established taking those values as reference.

In the elastic linear analysis, the ordinates of the elastic response spectra will be reduced by the behaviour factor, q, which takes into account the energy dissipation and the displacement ductility capacity of the building, as well as the damage limitation requirements.

The behaviour factor of the building will be established for each specific case, taking as a basis the values prescribed in codes for new structures and considering the typology of the building and the construction quality (materials, construction details, connections, etc.).

Depending on the mechanical characteristics of the units and of the mortar, and the possible presence of steel connecting elements, reference values q_0= 1.5 to 2.0, are, usually, adequate. In particular cases of flexible walls (like those referred in Fig. 12), higher values can still be adopted.

The q_0 values will still be multiplied by a corrective factor that takes into account the existing over-strength of the building (α_u / α_1). The corrective factor will be taken as 1.5 for buildings composed by bearing walls, placed in various directions, and intermediate diaphragms, effectively connected together, and as 1.2 in similar buildings when that effectiveness is not guaranteed. In the other situations, the corrective factor will be taken as 1.0.

4.5.3 Partial factors for actions

The partial factors for actions, γ_f, will be, in principle, those prescribed in the codes for the design of new structures.

In the case of permanent actions lower values can be adopted, when they are obtained through an exhaustive survey of the building, in which case the value γ_f = 1.2 is appropriate. For the seismic action, a partial factor, γ_f = 1.0, will, in general, be adopted.

4.6 Safety evaluation

The evaluation of the structural safety of the heritage building will be, in principle, carried out, as for new buildings, comparing the design values of the strengths of the materials (or of the elements), R_d, with the design values of the effects of the actions, E_d, for the appropriate combinations of actions.

As referred to above, the results of the modelling of heritage buildings are, in principle, not as reliable as in the case of new structures. An important action to be undertaken will, thus, be the evaluation of the consistency of those results, comparing them with the existing situation on the building, namely, the existing damage.

When this consistency is not clear enough, the structural safety of the building should be established not only on the basis of the results of the modelling, but through an integrated and holistic evaluation, in which other elements of information, namely the history of the building and the results of the visual survey of the building, will be considered. As a result, the assumptions adopted on the modelling of the building can also be adjusted, being the results obtained, modified.

In fact, history is a very powerful and complete laboratory, as it shows how the type of structure, the materials used, the connections between elements or the additions and alterations introduced, have reacted with time to particular events, such as, excessive loads, temperature variations, or earthquakes, which allows for extrapolations for the future.

On the other hand, the condition of the building can be evaluated by comparing it with that of similar buildings, whose behaviour has dully been evaluated. In fact, having observed the behaviour of different buildings with different states of degradation and damage caused by different phenomena, and having evaluated their safety, it is possible, on the basis of the survey of a specific building, to extrapolate that knowledge in the evaluation of that building.

It is the combined analysis of all existing pieces of information, in which quantitative and qualitative aspects are considered, that will lead to the best judgement about the structural safety of the building.

On figure 25 a flowchart of the actions to be undertaken in the structural assessment of a heritage building is presented.

From this evaluation one should conclude if the structural safety of the building is sufficient, or if rehabilitation works are necessary, and with what extent.

If the evaluation does not allow a clear conclusion to be obtained about the possible lack of safety of the building or of some of their structural elements, it will be wise not to intervene, in order to keep, as much as possible, the cultural value of the building. Furthermore, the cost of the intervention will be reduced.

In these situations, the building should be kept under observation (monitoring), until the situation becomes clearer.

Another solution, possible in some situations, will be to impose restrictions on the use of the building, which will allow for the reduction of the risk associated to an eventual lack of safety, as has been referred to above.

This kind of attitude should always be adopted in the case of buildings of high cultural value (monuments, etc.), if the required seismic resistance leads to unacceptable architectural alterations. In these situations the philosophy of “better something than nothing” should be followed.

Situations also exist in which the safety of the building is acceptable at the time of the assessment, but, as it is progressively decreasing, after a certain period of time it may not be acceptable (settlement of the foundations, for example). In this case a model should be developed to describe the evolution of the phenomena in order to foresee if, and when, it will be necessary to intervene.

When the building will be strengthened, the enhancement conferred by the prescribed measures should be evaluated through the modelling of the building, introducing the strengthening measures in the structural model (or models) adopted for the evaluation of the structural safety of the building.

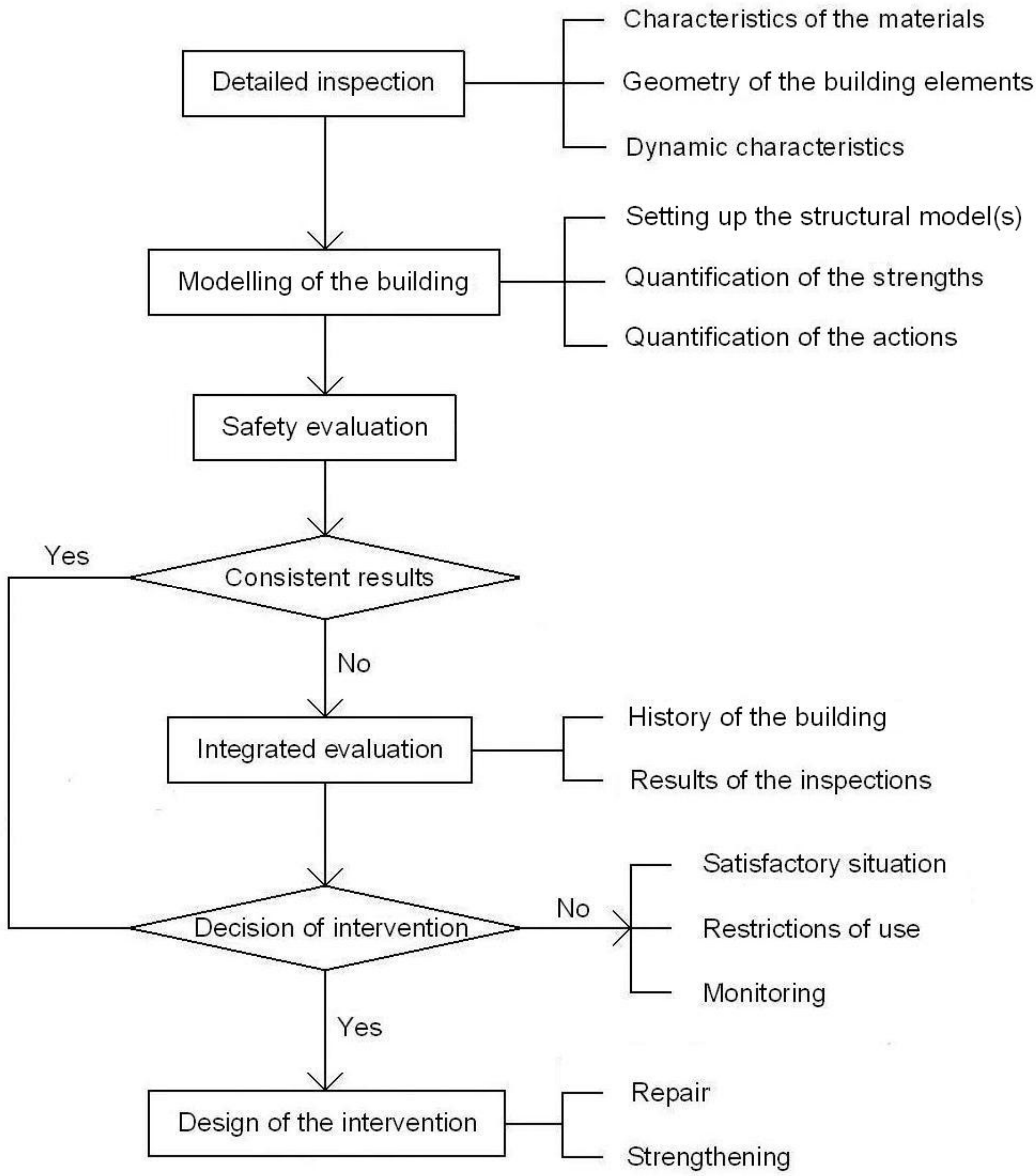


Figure 25: Flowchart of the actions to be undertaken in the phase of the structural assessment of the building (37)

The actions carried out for the structural assessment of the building should be documented in a report, in which all considerations and justifications for the options and decisions taken should be presented.

5 REPAIR AND STRENGTHENING

5.1 The design of the rehabilitation works

The design of the work for the structural rehabilitation of heritage buildings will be similar to the design of new buildings, consisting of written documents and drawings to enable the execution of the works.

The design can be developed in phases, as for new buildings (preliminary design, execution design, etc), but, in general, it will be developed in a single phase, after, and as consequence of, the structural assessment that has been carried out on the building.

The works proposed for the intervention should be accompanied by detailed specifications for their execution, namely about the materials to be used and their conditions of application, the phases of execution, and the equipment necessary. An estimate of the cost of each work, established in a realistic way, should also be included.

In the case of buildings that continue to be used during the execution of the works, that fact should be taken into account in the establishment of the phases of the execution and in the estimate of the costs.

The rehabilitation works can be of two kinds: repair, when the purpose is simply to restore the load-bearing capacity of the building elements, and strengthening, when the purpose is to increase the load bearing-capacity. When strengthening measures are adopted, their efficiency should be demonstrated through the modelling of the building, as referred to in section 4.

The choice of the solution to be adopted for an intervention of rehabilitation should be justified and be the object of cost-benefit analysis, in order to provide an efficient design at a cost as low as possible, whilst respecting, as much as possible, the cultural value of the building.

The huge research effort carried out around the world, during the last decade, with the purpose of evaluating the performance of solutions for the repair and/or strengthening of structures, in particular of heritage buildings, should not be overlooked. As a result, there are, nowadays, multiple solutions that have proved to be efficient for the repair or the strengthening of heritage buildings, depending on the defects to be corrected.

In the following clauses, the most common solutions for the repair of building materials and for the strengthening of building elements are presented, as well as solutions for upgrading foundations and for the improvement of safety against earthquakes of heritage buildings.

5.2 Repair of the degradation of materials

The repair of the degradation of building materials is, in general, achieved through the restoration of the geometry of the structural elements. When the loss of a section is not very significant, it will be sufficient the adoption of protective measures of the existing materials.

When restoring the geometry of elements, in principle, materials identical to the original ones should be used. The use of new materials should take into account the type of the original material and the defects that are associated with it.

a) Masonry

The repair of masonry elements is, in general, obtained through re-pointing the cracks with mortar, or the injection of appropriate grout (Fig. 26). Sometimes, the appropriate solution will include the replacement of the deteriorated masonry units.

Figure 26: Injections of epoxy resins in a masonry vault (21)

The composition of the mortar or the grout to be used (cement, resin, etc.) will depend on the characteristics of the masonry, itself. Particular attention should be given to the compatibility of the repair materials and the existing masonry.

For example, in the repair of masonry built with mortar that contains gypsum, mortar or grout of cement should not be used, because of the reaction between the gypsum and the cement.

For the superficial repair of a masonry element, chemical emulsions (silicates, etc.) can be used. The appropriate solution should be analysed in each case, depending on the specific conditions.

For the elimination of bio-deterioration in masonry elements, several solutions also exist, nowadays, (biocides, laser, etc.). The appropriate solution should also be analyzed in each specific case.

The elimination of infiltration of water and the rise by capillarity of moisture in the masonry, coming from the foundations is, in general, difficult to achieve. The injection of hydro-active grouts, based on polyurethane resins is, sometimes, adequate. When possible, the best solution will be, always, the elimination of the source of contamination, through the adequate drainage and desalinization of the soil.

b) Timber

Concerning the action of xylophages insects, preservative materials with insecticide properties exist nowadays, and are adequate for timber protection.

Concerning the effect of moisture on the outside of elements of coverings and of the floors embedded in walls, an adequate solution will be their protection against the infiltration from rain water. When those elements have deteriorated significantly they should be substituted by new ones.

For the problem of the existence of longitudinal cracking in timber elements, some solutions also exist, such as the use of lateral fastenings or ties, or the injection with special products (synthetic resins, etc.). When steel elements are used in this strengthening, they should be adequately protected against corrosion. When consolidating materials are used in timber, their compatibility should also be verified.

c) Steel and iron

The main problem with steel or iron elements is corrosion. Their repair requires, firstly, the elimination of the rust, for which several techniques exist (sand blast, etc.), then covering of the surfaces with appropriate products, usually, paint.

When there is a significant reduction of their sections, structural elements should be substituted by new ones. Depending on the specific conditions, reductions of more than 20% are, in principle, considered significant.

5.3 Repair and strengthening of the structural elements

The repair and strengthening of structural elements affected by mechanical actions usually requires the introduction of additional components in order to restore or increase their strength. In particular situations, partial demolition followed by the reconstruction of the elements, using, as much as possible, techniques identical to the original ones, can also be adequate.

a) Walls and columns

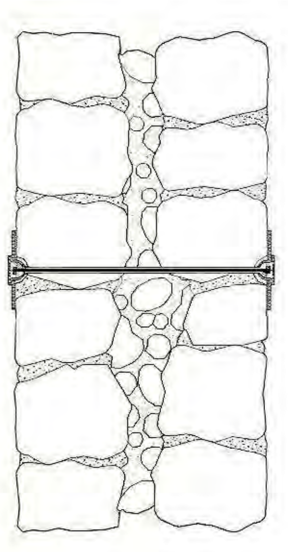


Figure 27: Strengthening of a masonry wall with steel connectors (27)

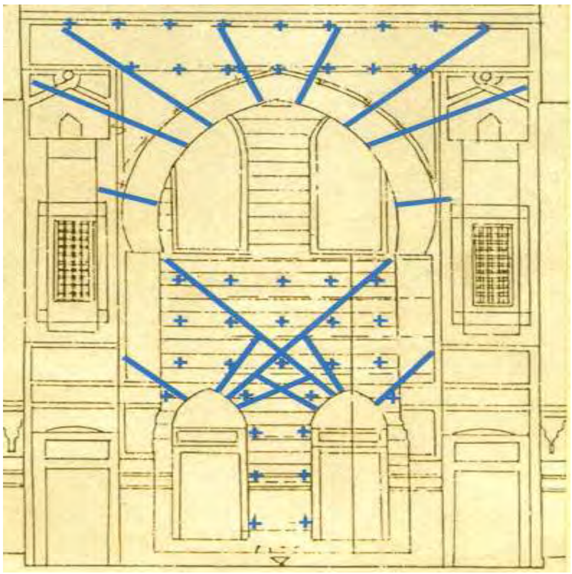
Concerning walls, to counteract the effects of vertical loads, the most efficient measures are the consolidation of the material itself, through injection or re-pointing, as has been referred to for the masonry material.

In the case of composite walls, with two exterior skins and an interior core (usually, rubble of low quality), steel connectors, anchored in the exterior skins constitute an efficient measure to assure their integrity, impeding their separation from the interior core (Fig.27).

When the walls are cracked due to in-plane loading, an adequate solution will be the installation of anchorages (anchor bolts) in the thickness of the wall, crossing the cracks (Fig. 28a; see, also, Fig. 34).

In particular situations it can be adequate to simply clamp the cracks with appropriate clamps, anchored on the surface of the wall (Fig. 28b).

To counter the effects of lateral loads on walls they can be strengthened with metallic reinforcement or strips of composites: carbon fibres (CFRP) (Fig. 29), glass fibres (GRC), etc., applied on their faces. In some situations, strutting can also be adequate.



a) With anchor bolts (21)

b) With clamps in cracks (21)

Figure 28: Strengthening of masonry walls for in-plane actions

In the case of buildings with timber floors, an important measure will be the improvement of the connections of the walls to the floors with metallic elements, envisaging, in particular, the seismic strengthening (see, Fig. 37 and Fig. 38). These metallic elements should be adequately protected against corrosion.

Concerning columns, injection, the application of ties and lateral confinement by wrapping with metallic sheets or composites (CFRP, GRC, etc.) are the measures usually used. The best solution will depend on the specific conditions.

b) Arches, vaults and domes

For this type of element, in addition to the injection and the re-pointing (as referred to for walls), other measures can be adopted, such as the introduction of tie-rods, generally, in steel, to compensate for the thrust induced on the supports (Fig. 30).

Figure 29: Strengthening of a masonry wall with glued CFRP strips (21)

The tie-rods should be placed, preferably, at the level of the bearing (in arches and vaults), or along parallel circles (in domes). They should be installed with a slight degree of pre-stressing, in order to guarantee that they will always be under tension.

When it is possible to install, another solution will be the jacketing of the extrados of the vaults with strips of glued composite materials. However, in this case, attention should be paid to the barrier effect that is created along the vault.

An alternative solution, very useful in particular situations, will be the insertion of strengthening components (in steel or timber), glued to the extrados of the masonry, which provides stiffness to the vault and in which the barrier effect is much less sensitive (Fig. 31).

Figure 30 Tying of masonry vaults with tie-rods in steel (21)

Figure 31: Strengthening of masonry vault with timber ribs glued on the extrados (8)

When blocks have become out of position, an adequate solution will be dismantling, followed by rebuilding in the correct position. In very severe situations, when the shape of the element has been heavily changed, it can be more appropriate to demolish the element, followed by its reconstruction using materials similar to the original ones.

In the case of filled vaults, one possible solution will be the reduction of weight or, if appropriate, the adjustment of its distribution.

In the case of floors made with brick vaults supported on steel beams, an adequate measure to restrict their lateral separation will consist in the placing of tie-rods, in steel, welded onto the bottom flange of the beams.

c) Towers and chimneys

The most common solution for the strengthening of this type of element consists ofn tying them with horizontal ties, usually, steel strips or cables (Fig. 32), or by wrapping them with glued composites (CFRP, GRC, etc.).

In the case of prismatic towers an appropriate measure will be the provision of diaphragms (in concrete or steel), at intermediate levels, for the confinement of the walls.

Figure 32: Tying of masonry tower with steel strips (21)

d) Framed elements

In the case of timber elements the most common solution for their strengthening is the substitution of the damaged elements by new ones.

Sometimes, the existing members can be strengthened, for example, through the gluing of strips or wraps of composites: CFRP, etc. (Fig. 33).

In the case of steel elements the best solution will also be the substitution of the damaged members by identical new ones, eventually, stronger.

Figure 33: Strengthening of timber floor with composites (20)

5.4 Upgrading of foundations

Concerning the strengthening or underpinning of foundations of walls or columns, the traditional technique of constructing piers in pits is still common.

The use of micro piles (Fig. 34) and the improvement of the soil through injection with jet-grouting or with hydro-active grouts are solutions that are also becoming increasingly popular. However, when these types of measures are adopted, they should be extended to the entire building, in order to avoid differential deformation of the building. Injection has the advantage of the creation of a barrier to protect the capillary rise of water to the building.

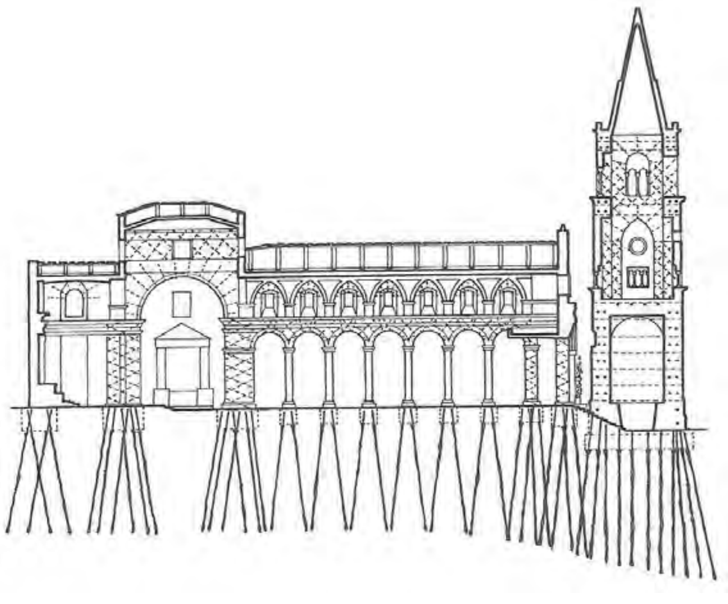


Figure 34: Strengthening of foundations with micro-piles (4)

Another solution, sometimes possible, is the widening of the foundation, usually, with additional reinforced concrete elements. In this case, it will be necessary to effectively connect the old and the new elements.

To avoid the cracking of buildings during excavations (for the execution of tunnels, for example), beams in reinforced concrete can be constructed under the walls and columns, in order to transmit the weight of the building to the surrounding soil, during the execution of the works.

Concerning arches, vaults and

domes, when they are subjected to differential settlement of the foundations, underpinning, using solutions identical to those referred for walls and columns should be carried out.

When towers and chimneys are subjected to differential settlements, the solutions referred to above can also be used. Sometimes, the adequate solution will be the increasing of the deformability of the soil in the zone where it is more rigid, for example, through the execution of horizontal holes in the soil (as it has been done on the tower of Pisa, for example).

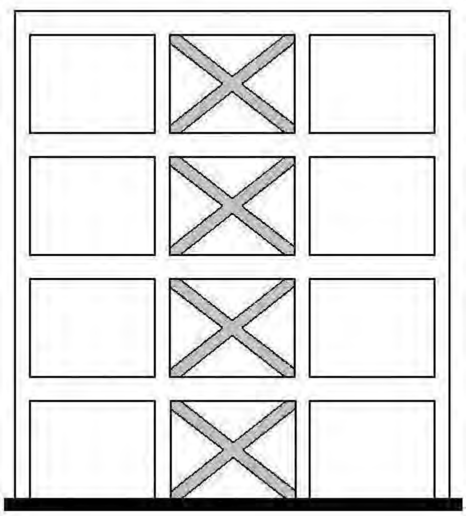
The upgrading of foundations for framed elements can also be achieved using solutions identical to those referred to above for walls and columns.

5.5 Improvement of safety against earthquakes

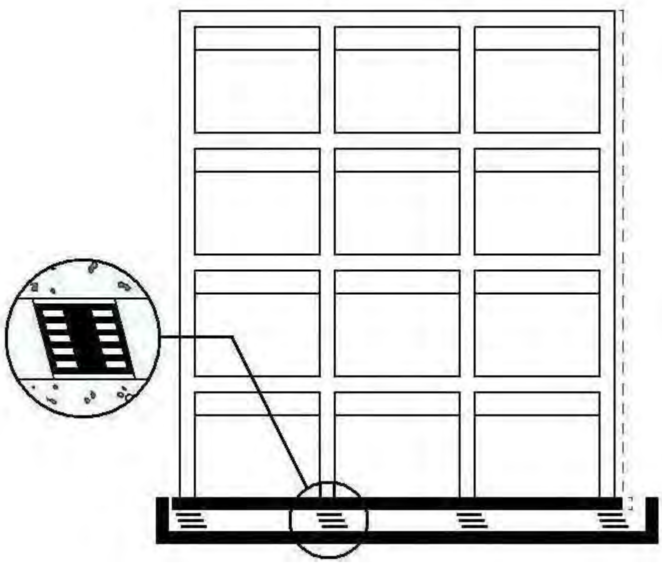
The improvement of the safety of heritage buildings against earthquakes can be obtained by intervening, at least in one of the two following areas: resistance or ductility. The main problem is that these types of intervention are, in general, very intrusive and also very costly.

In the case of buildings in which elements are required to be strengthened, an adequate solution will be the local strengthening of those elements, as has been referred to above in relation to the effect of mechanical actions.

Another possible solution will be the insertion of additional very stiff elements into the building, such as shear walls or diagonal stiffening elements (Fig. 35a), but these solutions are, in general, very intrusive.



a) With diagonal elements (21)



b) With base-isolation (21)

Figure 35: Solutions for the improvement of the safety against earthquakes

An alternative solution will consist in building an additional, autonomous, resistant system (in steel, for example), connected to the existing building, in order to assure combined behaviour of the two systems under earthquakes.

In the case of buildings with great importance, it can be adequate to introduce dissipative devices, such the isolation of the building on its base, through energy dissipating bearings on the foundations (Fig. 35b). Another possibility will be the installation of visco-elastic dampers in the connections between the main parts of the building, or the insertion of additional diagonal elements (similar to that on Fig. 35a).

Elimination of existing irregularities in the building, namely, the distribution of stiffness, strength, or mass, will also be a positive measure, but it will be possible only in buildings without significant cultural value. In any case, the reduction of dead weights in floors and roofs (filling cabinets, etc), when possible, is usually beneficial for the building.

Relatively simple measures also exist that, although not completely solving the problem, can significantly improve the safety of a building against earthquakes.

They are the measures aimed at insuring that the building behaves as a whole, through the realisation of good interaction between walls and floors, in order to achieve the "box-effect" in the building.

The most common solution is the insertion of tie-rods, whether metallic or of other material, (as referred to for arches and vaults), placed in the two principal directions of the building, at the level of floor diaphragms, and corresponding to bearing walls, anchored to the masonry by plates (Fig 36).

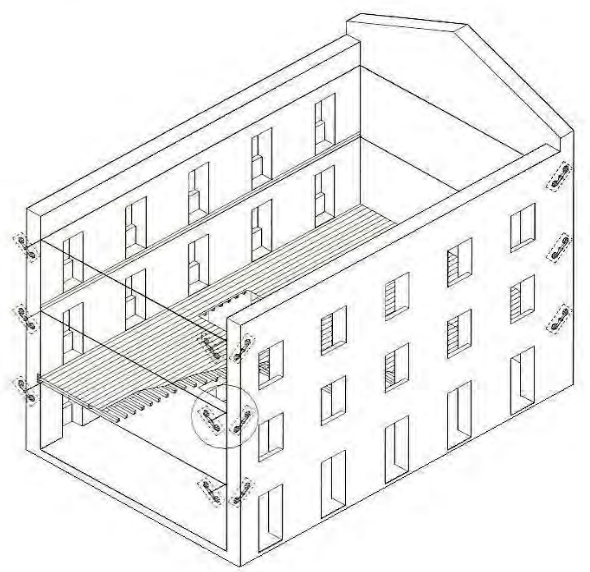


Figure 36: Tying of the building with tie-rods for the achievement of the "box-effect" (27)

Another possible solution will consist in the insertion of devices, usually in steel, to make and effective connection between the walls, and the walls and the floors, in the corners (Fig. 37).

Figure 37: Steel device to connect a wooden floor with walls integrating wooden elements (21)

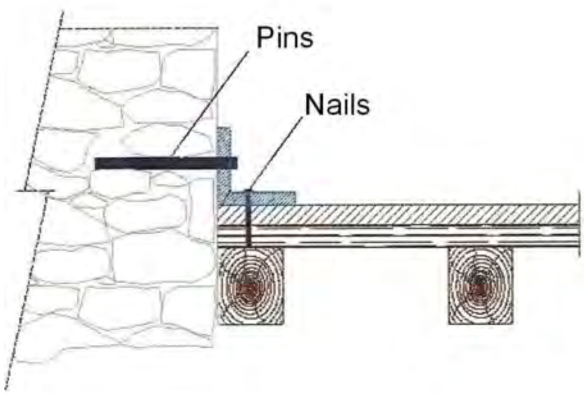


Figure 38: Connection system between wooden floors and masonry walls (41)

Another solution will be the installation of ring beams in the periphery of the floors, connected to the masonry walls with pins (Fig 38).

When the floors have limited stiffness to act as diaphragms, they should also be strengthened, for example, through the placing of another plank floor over the existing one (Fig. 38).

Buildings that are leaning one on another, should be treated as a whole, because the seismic behaviour of each one will depend on the behaviour of them all, but the consequences for each one can be very different (Fig. 39).

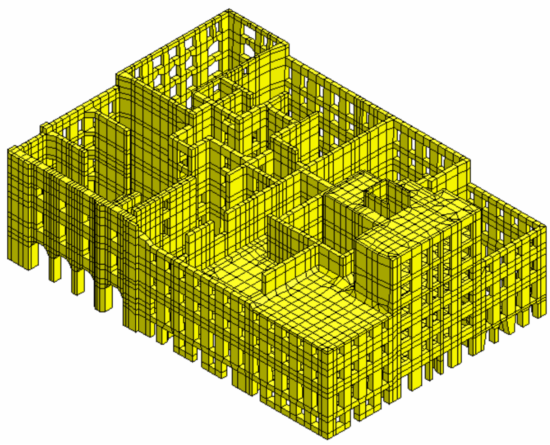


Figure 39: Finite element mesh for the analysis of a quarter of buildings (24)

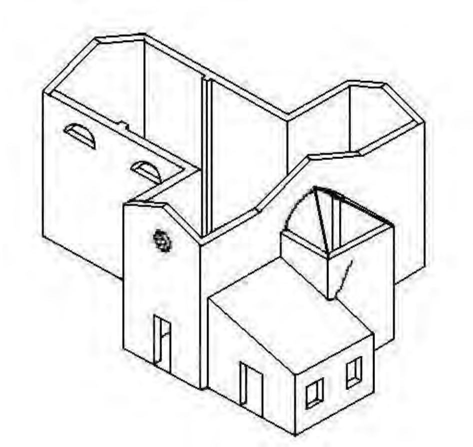


Figure 40: Macro-modelling of an ensemble of buildings (36)

However, as referred to in section 4, owing to the complexity of the structural system obtained and to the possible absence of rigid horizontal elements in many parts of the assemblage, macro-modelling will be, in principle, the most appropriate for this type of situation (Fig. 40).

6 QUALITY OF THE INTERVENTION WORK

6.1 Quality control of the execution of the work

The intervention work for structural rehabilitation of heritage buildings should be planned and be executed accompanied by a quality control plan, to be implemented during the execution of the works.

The quality control plan should describe the objective of each control operation and indicate the equipment of control to be used. On the intervention for structural rehabilitation, only solutions whose quality can be verified or controlled in situ, should, thus, be adopted.

In some situations it can be justified to carry out execution tests in the field, in order to assess the efficiency of the strengthening measures that have been adopted, as well as the adequacy of the modelling adopted in the structural assessment of the building.

In some cases it can be justified to install a monitoring system to observe the response of the building during the execution of the works, or for the control of its behaviour with time.

As a rule, all the actions carried out during any intervention of structural rehabilitation should be documented.

After the intervention, the building should be the object of a plan of conservation, with the carrying of periodic inspections, in order to identify any anomaly that has occurred in the meantime.

The building should also be the object of periodic operations of conservation (cleaning, etc.), in order to impede the progression of any deterioration that can occur, and thus, to avoid the degradation of the building.

As it has been said above, this strategy can ensure the structural safety of the building with less intrusive and lower cost interventions.

6.2 Qualification of the interveners

As referred to above, the intervention of structural rehabilitation of heritage buildings has many diverse implications, namely, architectural, structural, economic, historical and social, constituting a combination of technique and culture.

The intervention of structural rehabilitation of heritage buildings should, thus, be carried out by multidisciplinary teams, under the guidance of experts having both great technical capacity and cultural sensibility.

The teams for the inspection, the design and the execution of the works should also be staffed by qualified technicians, with specific knowledge in these areas.

In particular, the design engineer, besides having a high technical capacity, should have great sensibility for the cultural aspects of heritage buildings.

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