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Assessment and improvement of structural safety under seismic actions of existing constructions:
HISTORIC MASONRY BUILDINGS

STRUCTURAL SAFETY VS CONSERVATION: CONFLICTS AND COMPLEMENTARITIES

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Acre, International Conservation Center

ISRAEL ANTIQUITIES AUTHORITY רשות העתיקות

ועדת ההיגוי הבין-משרדית להיערכות לרעידות אדמה
National Steering Committee for Earthquake Preparedness

SCE

SUMMARY

1. GENERAL METHODOLOGY FOR STRUCTURAL ANALYSIS AND RESTORATION
2. SAFETY STANDARDS FOR HISTORICAL STRUCTURES
3. ACQUISITION OF DATA: INFORMATION AND INVESTIGATION
4. GENERAL REQUIREMENTS FOR INTERVENTION

Restoration was in the past reserved to monumental buildings. Restorers were few experienced professionals who took care for years and sometime for their professional life of the same monument or group of monuments.

After the second world war the historic centers in Italy were left to the poorest and to the immigrants lowering the level of **maintenance of historic buildings**.

On the other hand in high schools and universities, teaching of old traditional materials as **masonry** and wood was substituted by concrete, steel and new high-tech materials.

As frequently happened in the recent past, due to lack of knowledge and of appropriate analytical models, masonry was simply treated as a one material, as homogeneous as concrete, steel, or wood.

The assumption for masonry structures, especially, in seismic areas were that, they should **behave like a "box"** with stiff floors and stiff connections between the walls, no matter which was their geometry or material composition.

The strengthening project implied the use of the same **intervention techniques**: substitution of timber-floors and roofs with concrete ones, wall injection by grouts, use of concrete tie beams inserted in the existing walls.

Collapse of a repaired walls

Separation of leaves in a repaired stone masonry

Carefully considering what learned from the past and ongoing experiences, new concepts and tools are entering into codes and structural design practice:

- the differentiation of safety level for **different classes** of existing structures;
- assessment of **mechanical properties** of structures and materials with no real statistical evaluations (estimation based on limited data);
- **global and local models** to be used for structural analysis;
- evaluation of safety based on **pure equilibrium** considerations;
- use of **qualitative evaluation** of structural performances (observational approach: the existing structures as a model of itself);
- formalistic safety verifications: **improvement vs retrofitting**;
- limitation of interventions at the minimum possible level, depending on the **level of knowledge** of the structure and on the use of appropriate **investigations/monitoring** techniques;
- **removability** of the interventions and the **compatibility** of traditional/modern/innovative materials and construction techniques.

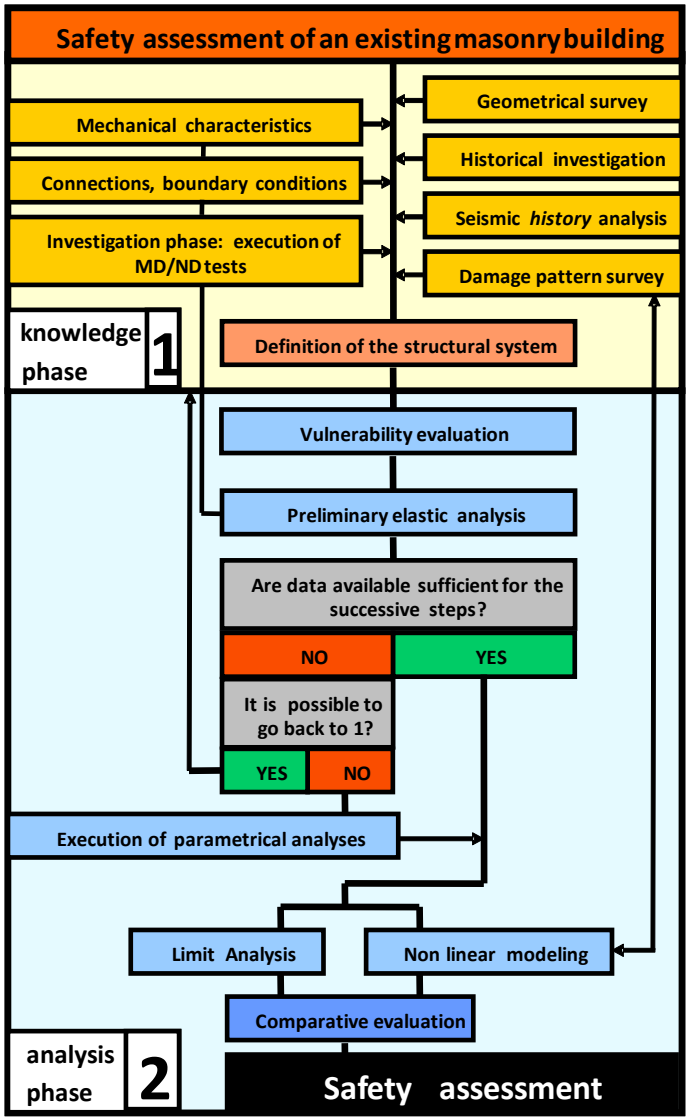
General methodology concepts are the achievement of the steps contained in phase:

1. **knowledge** of structure and materials

2. use of the obtained data for evaluation purposes

The two conceptually subsequent evaluation phases are not a one-way process, but feedback to the results of the structural analysis must come from the reiterative check of the evidences emerged in phase 1.

Data useful for the numerical analysis, but that can not be collected in the investigation process, will be parametrically evaluated by means of sensitivity analyses.



Structural safety of existing buildings (I)

EXISTING BUILDINGS: physical testimony of intangible assets and values

PRESERVATION and **USE** of historical buildings are two inseparable aspects:

- strengthening cultural identity

- preservation and improvement of the quality of life and economic well-being of the community that lives in a territory

PRESERVATION ↔ STRUCTURAL SAFETY ↔ USE

- inadequacy of the sophisticated procedures used
  for modern materials applied to perform assessments
  of structural safety of historic buildings;

- ineffectiveness of the techniques used to restore
  security after damages or to increase the security
  in order to satisfy requirements of new uses and codes

Structural safety of existing buildings (II)

STRUCTURAL SAFETY

conventional process

VERIFICATION → RETROFITTING → SAFETY
(EVENTUAL)

at the end of the process the probability that the structure is safe is very high → the probability of occurrence of a collapse within the expected life of the structure is very limited

Instead of talking of safety, it would be better to talk of **RISK** and its **SOCIAL AND ECONOMIC ACCEPTABLE VALUE**, expressed in probabilistic terms

Structural safety of existing buildings (III)

EXISTING BUILDINGS

The building exists and it is theoretically possible to "measure" everything is needed to make accurate security assessments, **but**:

- variability of the types of **materials** used during the centuries
- impossibility to perform appropriate **tests** (in terms of type and number)
- inadequacy of the available **computational models** to evaluate the behavior under the effects of static and dynamic loads

For new constructions the extra cost of a **"conservative" design** is marginal.

In the case of an existing construction it **may even be unacceptable**, especially if the execution of an intervention, that in some cases can compromise details of artistic or historic value, could be avoided performing more accurate assessments.

Recent evolution of codes and guidelines

RILEM International Union of Laboratories and Experts in Construction Materials, Systems and Structures

ICOMOS International Council on Monuments and Sites

- ISCARSAH International Scientific committee for Analysis and Restoration of Structures of Architectural Heritage

CEN European Committee for Standardization

- Technical Committee TC 346 (Conservation of Cultural Property)

ISO International Organization for Standardization

ISO 13822 – bases for design of structures – assessment of existing structures (first edition 2001)

UNI Ente Italiano di Unificazione

- "Cultural Heritage" commission

Recent evolution of codes and guidelines

Codes

- **ISO 13822** – bases for design of structures – assessment of existing structures (first edition 2001)
- **Italian code** for the design, assessment and seismic retrofitting of buildings – Chapter 11 (2003)
- **prEN 1998-3 Eurocode 8** – Design of structures for earthquake resistance Part 3 assessment and retrofitting of buildings

Guidelines

- **Iscarsah** Recommendations for the analysis, conservation, and structural restoration of architectural heritage
- **Italian guidelines** for the assessment and the reduction of seismic risk of cultural heritage

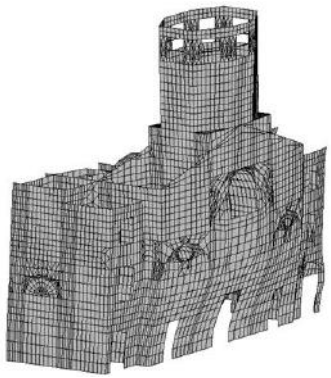
ISO 13822

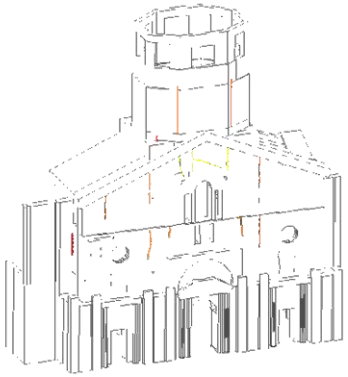
- The continued use of existing structures is of great importance because the built environment is a huge economic and political asset, growing larger every year. The **assessment of existing structures** is now a major engineering task.
- The structural engineer is increasingly called upon to devise ways for extending the life of structures whilst observing tight cost constraints.
- The establishment of **principles for the assessment of existing structures** is needed because it is based on an approach that is substantially different from the design of new structures, and requires knowledge beyond the scope of design codes.
- The ultimate goal is to **limit construction intervention to a strict minimum**, a goal that is clearly in agreement with the principles of sustainable development.

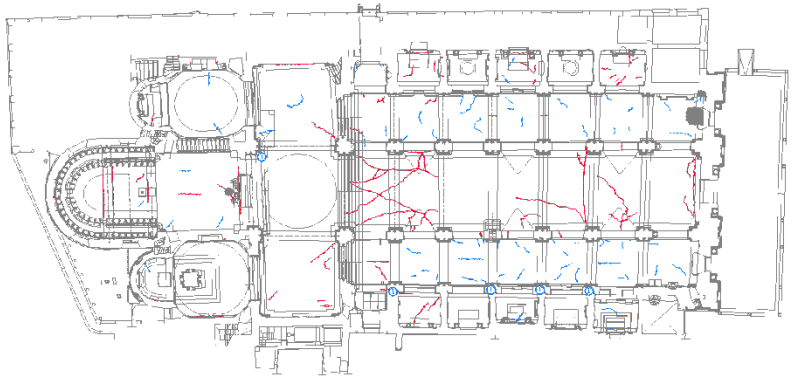
ISO 13822 – § 7.4

The conclusion for the assessment shall withstand a **plausibility check**. In particular, discrepancies between the results of structural analysis (e.g. insufficient safety) and the real structural condition (e.g. no signs of distress or failure, satisfactory structural performance) shall be explained.

Note: many engineering models are **conservative** and cannot always be used directly to explain an actual situation.







ISO 13822 – § 8.1

Safety assessment: structures designed and based on earlier codes, or designed and constructed in accordance with good construction practice when no codes applies, may be considered safe to resist **actions others than accidental actions** (including earthquake) provided that:

- Careful inspection does not reveal any evidence of significant damage, distress or deterioration
- The structural system is reviewed, including investigation of critical details and checking them for stress transfer
- The structure has demonstrated satisfactory performance for a sufficiently long period of time for extreme actions due to use and environmental effects to have occurred
- Predicted deterioration taking into account the present condition and planned maintenance ensures sufficient durability
- There have been no changes for a sufficiently long period of time that could significantly increase the actions on the structure or affect its durability, and no such changes are anticipated

Recommendations for the analysis, conservation and structural restoration of architectural heritage

Guidelines

1. *General criteria*

2. *Acquisition of data: Information and Investigation*
   - *2.2 Historical and architectural investigations*
   - *2.3 Investigation of the structure*
   - *2.4 Field research and laboratory testing*
   - *2.5 Monitoring*

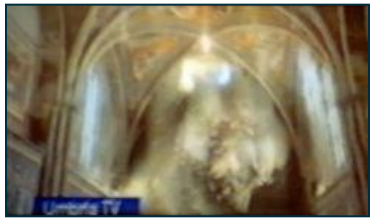
3. *Structural behaviour*
   - *3.1 General aspects*
   - *3.2 The structural scheme and damage*
   - *3.3 Material characteristics and decay processes*
   - *3.4 Actions on the structure and the materials*

4. *Diagnosis and safety evaluation*
   - *4.1 General aspects*
   - *4.2 Identification of the causes (diagnosis)*
   - *4.3 Safety evaluation*
     - *4.3.1 The problem of safety evaluation*
     - *4.3.2 Historical analysis*
     - *4.3.3 Qualitative analysis*
     - *4.3.4 The quantitative analytical approach*
     - *4.3.5 The experimental approach*
   - *4.4 Judgement on safety*

5. *Decisions on interventions - The Explanatory Report*

Guidelines for the assessment and the reduction of seismic risk of cultural heritage

- CHAP. 1: OBJECT OF THE GUIDELINES
- CHAP. 2: SAFETY AND CONSERVATION REQUIREMENTS
- CHAP. 3: SEISMIC ACTION
- CHAP. 4: BUILDING KNOWLEDGE
- CHAP. 5: MODELS FOR SEISMIC SAFETY ASSESSMENT
- CHAP. 6: SEISMIC IMPROVEMENT AND INTERVENTION TECHNIQUES CRITERIA
- CHAP. 7: RESUME OF THE PROCESS



Sequence of the collapse of the vault of the Assisi Basilica during the 1997 earthquake

Italian Guidelines – § 1 – Object of the Guidelines

Among the "**relevant buildings**" the guidelines consider those buildings that collapsing can determine significant damages to the historical and artistic heritage: in these cases the concept of "tight cost constraints" becomes much broader, as in the cost also the **loss of artistic and historic values** must be taken into account.

The document intend to define the process of **knowledge**, the methods for **risk assessment**, the criteria for the design of **intervention**, according to the Italian Code, but adapted to the needs of cultural heritage masonry buildings.

For those buildings, it is possible to proceed with **improvement** interventions.
In this case it is anyway required the assessment of the safety level reached after the intervention: this is useful in order to define the minimum intervention or the need for intervention. For **strategic and relevant CHBs**, the reduction of seismic protection level related to the improvement cannot be always accepted.

For the conservation of cultural heritage in seismic area, **different levels of assessment**, with different aims, are foreseen: for these types of evaluation, different analysis tools are made available.

Guidelines for the assessment and the reduction of seismic risk of cultural heritage

ITALIAN GUIDELINES

interventions on preserved buildings should be designed to "**improve**" and not to "retrofit" their structural performance

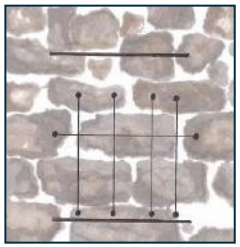
it is necessary to express a positive **opinion** on the relationship between the achieved safety level, through an intervention consistent with the needs of conservation, and the reference protection level, which is desirable with reference to the conditions of use; this assessment will be expressed in global terms, **not only on the basis of a numerical comparison** between collapse acceleration and expected acceleration at the site, **but also considering other aspects that were qualitatively evaluated** and cannot be explicitly considered in the calculation

ASSESSMENT - IMPROVEMENT ↔ ~~**VERIFICATION - RETROFITTING**~~

Interdisciplinary approach that goes beyond simple technical considerations.
Investigating team: incorporates a **range of skills** appropriated to the characteristics of the building.

WHY MULDISCIPLINARY INVESTIGATION IS NECESSARY?

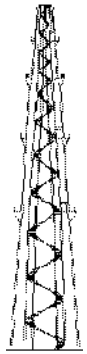
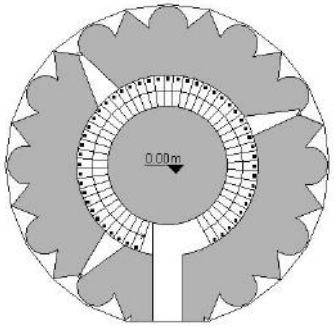
- the **knowledge** of the old building construction technique and materials was lost during the last century, therefore it has to be rebuilt;
- buildings belong to **construction typologies which are different** according to the building use and to the local materials;
- **masonry** is a composite with different section morphology: one-two-three leaves, regular irregular, made with brick and/or stones
- analytical models should be **calibrated** by experimental investigation and applied appropriately to check the structural safety.





This **knowledge** can be reached by:

- description of the structure's **geometry** and construction;
- definition, description and understanding of building's **historic and cultural significance**;
- description of the original **building materials and construction techniques**;
- historical research covering the entire life of the structure including both changes and any **previous structural interventions**;
- description of the 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 survey of the **site**, soil conditions and environment of the building.

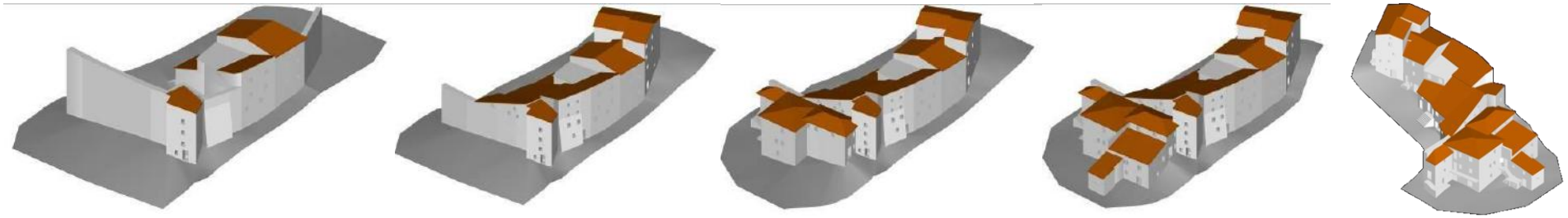

Historical and architectural investigations: the purpose is to understand:

- conception and the significance of the building,
- techniques and skills used in its construction,
- subsequent changes in both the structure and its environment
- any events that may have caused damage.

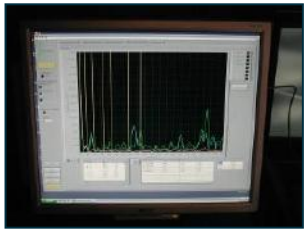
Survey of the structure: direct observation is an essential phase of the study:

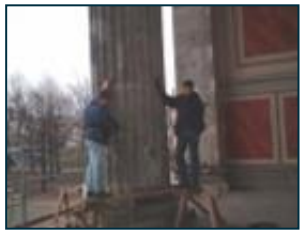
- identifying decay and damage,
- if phenomena have stabilised,
- determining immediate risks and urgent measures to be undertaken,
- identifying environmental effects on the building.

Record drawings should map different kinds of materials, any decay and any structural irregularities and damage, paying particular (but not exclusive) attention to crack patterns and crushing phenomena.



Field research and laboratory testing: Tests usually aim to identify the various mechanical, physical and chemical characteristics of the materials, the stresses and deformations of the structure and the presence of any discontinuities within it.
Non-destructive tests should be preferred to those that involve alterations to a structure.


Monitoring: allows to evaluate the structural behaviour of the structure over a period of time, not only to acquire useful information when progressive phenomena is suspected, but also to schedule of the maintenance works and indicate the possible necessity of strengthening or repair interventions, during a step-by-step procedure of structural renovation.
Monitoring activities start with the basic visual inspection, to evaluate macroscopic changes in the structure (damage pattern onset, widening of existing cracks…), until sophisticated electronic controls on significant mechanical or physical parameters.

To carry out the structural analyses, it is necessary to gain **proper knowledge** by means of surveys, historical researches, in-situ and laboratory tests:

BUILDING GEOMETRY

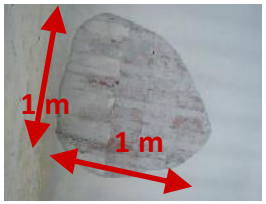
geometry, particular elements (crack pattern & out of plumbs)

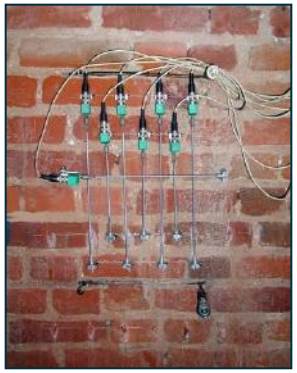
- by means of surveys

CONSTRUCTIVE DETAILS

connections, lintels, elements to counteract thrusts, vulnerable elements, masonry tipology

- limited *in situ inspection*
- extended & comprehensive *in situ inspection*





MATERIAL PROPERTIES

particularly aimed at the mechanical characterization of masonry, through inspections, NDT, MDT & DT

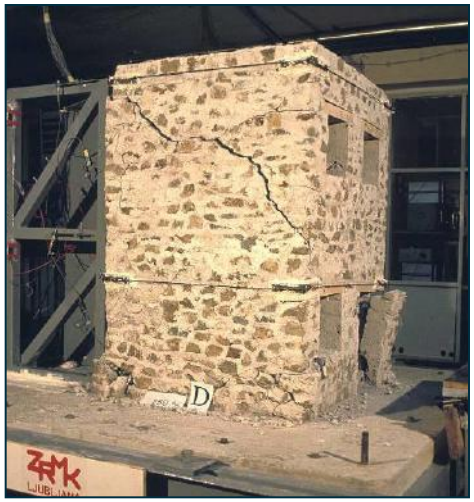
- limited *in situ testing* (inspections)
- extended *in situ testing* (MDT & NDT)
- comprehensive *in situ testing* (DT)

Decisions on intervention (I)

A **“to do list”** in case of strengthening intervention is **not viable**, since specific and effective intervention in one case can be ineffective or, even worst, detrimental to the seismic capacity of the structure in other cases.

In order to **respect the existing features** of the considered constructions special care has to be paid in order to limit in any case as much as possible variations not only of its external appearance, but also of its mechanical behavior.

Attention has to be focused on **limiting interventions to a strict minimum, avoiding unnecessary strengthening**, a goal that is clearly in agreement with the principles of sustainable development.

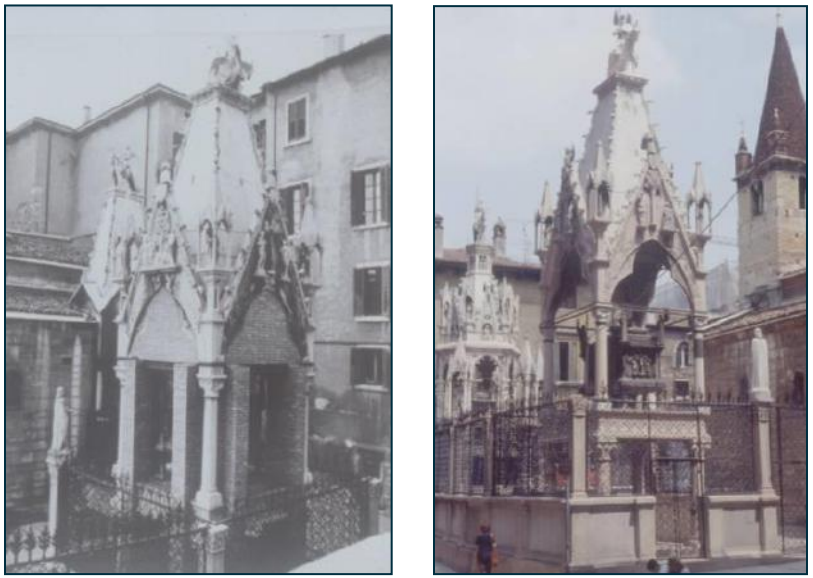


Tomaževič, ZRMK, Ljubljana, Slovenia

Decisions on intervention (II)

Efforts are needed to respond to "**conservative**" design criteria while intervening to ensure acceptable structural safety conditions of existing historic constructions.

This requires that it is necessary to analyze, theoretically and experimentally, the resisting properties of the considered construction, prior and after interventions are made, in order to **avoid over-designing approaches**.



Arche Scaligere, Verona, Italy Before and after intervention

The actual contribution of any **traditional/innovative material** and techniques, and of their possible combinations, can be adequately and scientifically exploited in order to ensure durability, compatibility and possibly removability of repair/strengthening interventions.

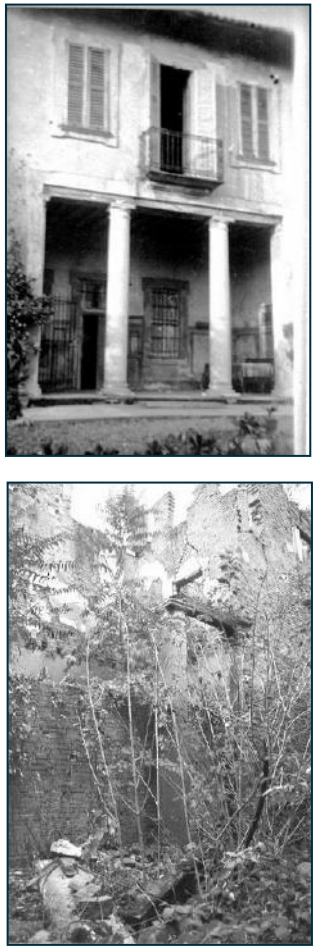
The basis for conservation and reinforcement must take into account both **safety evaluation** and understanding of **historical / cultural significance** of the structure.

Each intervention should, as far as possible, respect the **original concept and construction techniques**.

Where the application of current design codes would lead to excessive interventions that would involve the loss of historic fabric or historic character, it is necessary to provide adequate safety by alternative means.

Repair is always preferable to replacement.

Dismantling and reassembly should only be undertaken when required by the nature of the materials and structure and when conservation is more damaging.



Lack of maintenance: rural building in Milan in 1980 and 1998

- **Respect of the functioning of the structure**, generally intervening in well defined areas and avoiding to vary in a significant manner the global stiffness distribution.

- Interventions to be performed only after the **evaluation of their effectiveness** and the impact on the historical construction.

- Interventions have to be **regular and uniform** on the structures. The execution of strengthening interventions on limited portion of the building has to be accurately evaluated (reduction or elimination of vulnerable elements and structural irregularity…) and justified by calculating the effect in terms of variation on the stiffness distribution.

- Particular attention has to be paid also to the **execution phase**, in order to ensure the actual effectiveness of the intervention, because the possible poor execution can cause deterioration of masonry characteristics or worsening of the global behaviour of the building, reducing the global ductility.

The choice between "**traditional**" and "**innovative**" techniques should be determined on a case-by-case basis with preference to those that are **least invasive and most compatible** with heritage values, consistent with the need for safety and **durability**. When new products are used all possible negative side effects must be considered.

Interventions **should not be visible**, bur when that is impossible the aesthetic impact on the monument has to be carefully considered before taking any final decision.

Where possible, any measures adopted should be "**reversible**" to allow their removal and replacement with more suitable measures if new knowledge is acquired.

At times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest an **incremental approach** ('design in process'), beginning with a minimum intervention, with the possible adoption of subsequent supplementary measures.

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.

CRITERIA FOR THE PROPOSAL OF INTERVENTION S FOR THE IMPROVEMENT OF THE ARCHITECTURAL HERITAGE

- MINIMUM INTERVENTION
- PROGRESSIVE MEASURES (BY STEPS) AND CONTROL OF EFFICIENCY/NECESSITY
- LOCAL ACTIONS THAT DO NOT AFFECT THE STRUCTURAL RESPONSE
- REMOVABILITY
- ALLOWING / MAINTAINING REPAIRABILITY
- DURABILITY
- RELIABLE IN ITSELF 'AND INTERACTION WITH THE REST OF THE STRUCTURE
- USE MORE ALTERNATIVE MODELS AND ANALYSIS, VALIDATION / CALIBRATIONS

ASSESSMENT - IMPROVEMENT ↔ ~~**VERIFICATION – RETROFITTING**~~

FORCE-EQUILBRIUM - in addition to, and more than that - STRESS-RESISTANCE

THE MOST APPROPRIATE APPROACH TO STRUCTURAL SAFETY

OF HISTORIC CONSTRUCTIONS

BASED ON THE CONCEPT OF “IMPROVEMENT” RATHER “COMPLETE RETROFITTING”

TO BE INTENDED AS FIRST RECOGNIZING AND THEN VALORIZING (IN STRUCTURAL SENSE)

THE ORIGINAL CONSTRUCTION CHARACTERISTICS

USING WHERE POSSIBLE AND STRICTLY NECESSARY MINIMUM INTERVENTIONS WITH MINIMUM IMPACTS THEN NECESSARILY LOCAL AND VERY TARGETED

NOT ONLY SATISFIES CONSERVATION CRITERIA

BUT ALSO REPRESENTS THE BEST WAY OF SATISFYING THE BASIC REQUIREMENTS OF THE MECHANICS OF HISTORIC CONSTRUCTIONS

Thanks for your attention!

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