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GUIDELINES FOR END USERS INCLUDING BUILDING CODES AND STANDARDS



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NEW INTEGRATED KNOWLEDGE BASED APPROACHES TO THE PROTECTION OF CULTURAL HERITAGE FROM EARTHQUAKE INDUCED RISK

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NIKER GUIDELINES FOR END-USERS





GUIDELINES' PHILOSOPHY & APPROACH

- provide simple design rules, design formulations and design charts
- support assessment of single elements, connections & structure
- support passive interventions for improving earthquake resistance
- advice the best choice and application of active devices
- exploit and promote integrated methodologies



DELIVERABLES ORGANIZATION

Two main clusters can be distinguished:

1. GUIDELINES FOR TECHNICAL ISSUES (WP10.1)

- D10.1 Guidelines for design and execution of optimum interventions for end users

- D10.2 Guidelines for assessment and improvement of connections in buildings for end-users

- D10.3 Design and application guidelines for Stick-slip and Hysteretic dissipative anchors with embedded sensors

2. GUIDELINES FOR INTEGRATED METHODOLOGIES (WP10.2)

- D10.4 Guidelines for reliable seismic analysis and knowledge based assessment of buildings

- D10.5 Integrated methodology for effective protection and earthquake improvement of cultural heritage

Guidelines for design and execution of optimum interventions for end users

The aim is to outline the main procedures used during the project duration for assessing connections. These guidelines will provide insights on essential tests and modelling strategies exploited

VERTICAL **APPLICATION** ELEMENTS component, material, INTERVENTIONS prevented failure HORIZONTAL mechanism, repaired **ELEMENTS** damage **DEFINITION AND SCOPE APPLICABILITY CONDITIONS ADVANTAGES AND LIMITS EXECUTION PROCEDURES** • **IN-SITU CONTROLS RECCOMENDATION END REFERENCES**



EXAMPLE: VERTICAL ELEMENTS

VERTICAL ELEMENTS					
INTERVENTION	APPLICATION				
Туре	Component	Material	Prevented failure mechanism	Repaired damage	
Grout injection	Wall; pillar; vault; dome	Masonry (natural stone, brick with lime based mortar) Earthen material (adobe, rammed earth, cob)	Out-of-plane losses In-plane failure	Cracking repair; Improved bond; Layers connection; Enhanced strength	
Reinforcement with steel wires	Wall; pillar	Adobe and clay (adobe brick walls; dry and solid clay brick walls)	In-plane failure	Improve of in- plane stiffness Cracking	
Reinforcement using geo-nets	Wall; pillar	Adobe wall; dry and solid clay brick wall	In-plane and out-of -plane failure	Improve of in- plane stiffness; Cracking Ensure higher compactness of wall even after partial damage Applicable for retrofitting	
Reinforcement with Belts	Wall	Earthen material (adobe, rammed earth, cob)	In-plane failure	Improve displacement capacity	
Strengthening of traditional timber connections using bolts	Wall connection	Wood	Out-of-plane losses	Opening of connections	
Steel plates	Wall connection	Wood	Crushing of wood	Opening of connections Tearing off of beams and posts	
Steel flat bars inserted with NSM technique	Wall connection	Wood	Crushing of wood Out-of-plane losses	Opening of connections Tearing off of beams and posts	



Guidelines for assessment and improvement of connections in buildings for end-users

The aim is to outline the main procedures used during the project duration for assessing connections. These guidelines will provide insights on essential tests and modelling strategies exploited





ASSESSMENT METHODS





IMPROVEMENT OF CONNECTIONS

CONNECTIONS					
INTERVENTION		APPLICATION			
Ref. Section	Туре	Type of connection	Material	Prevented failure mechanism	Repaired damage / Improved performance
4.1	Grouted metallic anchor	Wall to wall	Brickwork masonry	Cracking at the joint of the two walls, overturning/out- of-plane failure of walls	Restored connection between vertical elements so as to ensure redistribution of loads depending on the stiffness of bearing elements and achieve better global performance
4.2	Grouted anchors	Wall to wall	Earthen materials	Cracking at the joint of the two walls, overturning/out- of-plane failure of walls	Restored connection between vertical elements so as to ensure redistribution of loads depending on the stiffness of bearing

	Grouted metallic anchors encase in fabric sock					
-	Design parameters	Applicability	Advantages and limits			
	Tensile strength of metallic anchor rod; Bond strength between anchor rod and binder; Bond strength between binder and parent material; Tensile strength of parent material; Bond strength at mortar joints	Generally applicable. In case of particularly weak or loose substrata, the performance of the strengthening system is improved by grouting of parent material.	Advantages - Negligible increase in mass; - No aesthetic impact; - Reversibility. Limits - Presence of precious finishes and geometry of the building might restrict prevent the possibility of drilling anchors in the required possibility of			



Design and application guidelines for Stick-slip and Histeretic dissipative anchors with embedded sensors

These guidelines defines the parameters for the best choice of dissipative devices depending on the type of the building, expected level of hazard, level of protection and performance. Details concerning design and possible application is presented

DESIGN AND IMPLEMENTATION OF ENERGY-BASED DEVICES FOR THE STRENGTHENING OF HISTORIC STRUCTURAL CONNECTIONS

- DESIGN PARAMETERS
- APPLICABILITY
- PROS AND CONS

- DISSIPATIVE ANCHOR DEVICES
- STICK-AND-SLIP CARPENTERY
 CONNECTIONS
- DUCTILE ANCHORS

APPLICATION

- component
- material
- prevented failure mechanism
- repaired damage



Guidelines for reliable seismic analysis and knowledge based assessment of buildings

These guidelines provides information regarding the monitoring and modelling techniques used during the project. Final recommendations are provided for supporting users in the selection of the most appropriate assessment strategy

KNOWLEDGE BASED ASSESSMENT PROCEDURE



- METHODS
- CRITICAL REVIEW
- FEASIBILITY OF METHODS
- EFFECTIVENESS OF APPLICATION IN REAL CASE STUDY

MODELLING

- METHODS
- CRITICAL REVIEW
- FEASIBILITY OF METHODS
- EFFECTIVENESS OF APPLICATION IN REAL CASE STUDY



Integrated methodology for effective protection and earthquake improvement of Cultural Heritage

The aim is to outline the integrated methodology necessary to obtain reliable Information concerning buildings. These guidelines support the users in following simple procedural details of monitoring, modelling and intervention methods





INTERNATIONAL GUIDELINES FOR RESTORATION AND CONSERVATION





UNIVERSITY OF PADOVA - Dept. of Civil, Environm. & Architect. Engineering

- Technical-scientific national and international organism affiliation
- **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)
- International Organization for Standardization
 ISO 13822 bases for design of structures assessment of existing structures (first edition 2001)
- **UNI** Ente Italiano di Unificazione
 - commissione "Beni Culturali"





International Council on Monuments and Sites

Conseil International des Monuments et des Sites



European Commitee for Standardization Comité Européen de Normalisation Europäisches Komitee für Normung







Analysis and restoration of historic buildings (I)

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 building**.

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.



Analysis and restoration of historic buildings (II)

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 timberfloors 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



Analysis and restoration of historic buildings (III)

Carefully considering what has be 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;
- the evaluation of safety based on pure equilibrium considerations;
- the use of qualitative evaluation of structural performances (observational approach: the existing structures as a model of itself);
- formalistic safety verifications: improvement vs retrofitting;
- the 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;
- the removability of the interventions and the compatibility of traditional/modern/innovative materials and construction techniques.



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 overdesigning 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.



Safety standards for historical structures

<u>Codes</u>

- ISO 13822 bases for design of structures assessment of existing structures (first edition 2001)
- Italian Building Code for design, assessment and seismic retrofitting Chapter 8: existing buildings (NTC 2008)
- 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 (2006)



Rules for study, diagnosis and safety evaluation (I)

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.



Rules for study, diagnosis and safety evaluation (II)

<u>ISO 13822 – § 7.4</u>

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.





Rules for study, diagnosis and safety evaluation (III)

<u>ISO 13822 – § 8.1</u>

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



Scientific methodology

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.







International Council on Monuments and Sites Conseil International des Monuments et des Sites



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. <u>Decisions on interventions The Explanatory</u> <u>Report</u>



Iscarsah Guidelines § 2 – Acquisition of data: Information and Investigation

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.













Iscarsah Guidelines – § 3 – Structural behaviour

The behaviour of any structure is influenced by:

- a) the structural form its quality and the connections between structural elements;
- b) the construction materials
- c) mechanical actions and chemical and biological actions.

Structural scheme and damage: the real behaviour of a building is too complex to fully model and it is necessary to represent it with a simplified 'structural scheme', i.e. an idealisation of the building.

Material characteristics and decay processes: Material characteristics (strength, stiffness...), the basic parameters for any calculation, may be reduced by decay caused by chemical, physical or biological action.

Actions on the structure and the materials:

	i) Static actions	a) Direct actions (i.e. applied loads)		
1 - Mechanical actions		b) Indirect actions (i.e. applied strains)		
	ii) Dynamic actions (imposed accelerations)			
2 - Physical, Chemical and Biological actions – acting on the materials				







Iscarsah Guidelines – § 4 – Diagnosis and safety evaluation

Modern codes of practice adopt a conservative approach involving the application of safety factors to take into account the various uncertainties. This is appropriate for new structures but it is not appropriate in historic structures where requirements to improve the strength may lead to the loss of historic value.

Diagnosis: identifies the causes of damage and decay, on the basis of acquired data.

Safety evaluation: methods of structural analysis used for new construction may be neither accurate nor reliable for historic structures and may lead to inappropriate decisions. This is due to such factors:

- difficulty in fully understanding the complexity of an existing building,
- uncertainties regarding material characteristics,
- unknown influence of previous phenomena (soil settlements...),
- imperfect knowledge of alterations and repairs carried out in the past.

A quantitative approach based on mathematical models cannot be the only procedure to be followed: it is the combined analysis of the information obtained which may lead to the 'best judgement'.



Iscarsah Guidelines – § 4 – Diagnosis and safety evaluation

Historical analysis: Knowledge of what occurred in the past can help to forecast future static and dynamic structural behaviour.

Although satisfactory behaviour shown in the past is an important factor for predicting the survival of the building in the future, it is not always a reliable guide.

Qualitative analysis: comparison between the present condition of the structure and that of other similar structures whose behaviour is already understood.

This approach (inductive procedure) is not entirely reliable because it depends more upon personal judgement than on strictly scientific procedures.

The quantitative analytical approach: modern structural analysis, on the basis of certain hypotheses (theory of elasticity, theory of plasticity, frame models, etc.), draws conclusions based on mathematical calculations.

Uncertainties on material characteristics and structural behaviour and simplifications adopted may lead to results not reliable and different from the real situation: mathematical models of damaged structure will help to evaluate safety levels.

Even when the results of calculations and analysis cannot be precise, they can indicate the flow of the stresses and possible critical areas.



Iscarsah Guidelines – Remedial measures and controls

Adequate **maintenance** can limit the need for subsequent intervention.

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



Iscarsah Guidelines – Remedial measures and controls

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.



Iscarsah Guidelines – § 5 Decisions on interventions: the explanatory report

Decisions regarding any interventions should be **made by the team** and take into account both the safety of the structure and considerations of historic character.

The **explanatory report** is a commentary upon the more detailed specialist reports. It needs to be a **critical analysis** of the steps and of the decisions taken by the team.

The purpose is to explain those things that cannot be reduced to calculations, making clear the reliability of the data, the hypotheses used and the **choices made in the design**, showing the obtained improvement in the structural behaviour.

Many of the steps in the process will involve a number of **uncertainties**, which must be explained in the report. Uncertainties include:

- The nature of the structural scheme;
- Knowledge of any weaknesses;
- The properties of the materials;
- The nature of the loading and other actions upon the structure.



<u> Iscarsah Guidelines – Masonry buildings</u>

The term masonry refers to **stone**, **brick and earth based construction** (i.e. adobe, pisé de terre, cob, etc.). Masonry structures are made of materials that have **low tensile strength** and may show cracking or separation between elements.

The analysis of masonry requires the identification of the characteristics of the constituents of this composite material: type of stone or brick, and type of mortar.

Masonry structures rely upon the effect of the **floors or roofs to distribute lateral loads** and so ensure their overall stability: it is important to examine the disposition of such structures and their effective **connection** to the masonry.

The main causes of damage or collapse are **vertical loads**; **horizontal forces** are usually produced by the thrust of arches or vaults and may become dangerous if not balanced by other structural elements (heavy walls and abutments, tie bars...). In seismic areas horizontal forces may become produce extensive damage or collapse.

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



<u>Iscarsah Guidelines – Masonry buildings</u>

Particularly attention has to be paid to **large walls** constructed of different kinds of material (cavity walls, rubble filled masonry walls and veneered brick walls with poor quality core): the **core material** may be less capable of carrying load and it can produce lateral thrusts on the faces. In this type of masonry the **external leaves** can separate from the core: it is necessary to determine if the facing and the core are acting together or separately.

Various strengthening interventions on walls are available:

- consolidating injection of the wall with **grout** (the appropriate fluid mortars based on lime, cement or resins depends on the characteristics of materials)
- repointing of the masonry,
- vertical longitudinal or transverse reinforcement,
- removal and **replacement** of decayed material,
- **dismantling** and rebuilding, either partially or completely.

Ties made of appropriate materials can be used to improve the load-bearing capacity and stability of the masonry.



<u>Iscarsah Guidelines – Masonry buildings</u>

Typical of masonry structures are **arches and vaults**: they are compression structures relying on their curvature and the forces at the abutments, allowing the use of materials with low tensile strength.

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

The relationship between load distribution and geometry of the structure needs to be carefully considered if loads (especially **heavy dead loads**) are removed or added.

The main **repair measures** include:

- addition of tie-rods (at the spring level in vaults, along parallel circles in domes);
- construction of buttresses;
- correction of the load distribution (in some cases by adding loads).









<u>Iscarsah Guidelines – Masonry buildings</u>

High-rise buildings such as **towers and minarets**, are often characterised by high compression stresses. In addition, these structures are further weakened by imperfect connections between the walls, by alterations such as the making or closing of openings. **Diaphragms, horizontal tie-bars and chains** can improve the ability to resist gravity as well as lateral loads.





<u> Iscarsah Guidelines – Timber</u>

Wood has been used in load-bearing and **framed or trussed structures** and in **composite structures** of wood and masonry.

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

Fungal and insect attack are the main sources of damage. In framed timber structures the main problems are related to local failure at the **joints**. Contact with masonry is often a source of moisture.

Chemical products can protect the wood against biological attack: where **reinforcing materials** or consolidants are introduced, compatibility must be verified.














Iscarsah Guidelines – Iron and steel

Cast iron and steel are alloys and their susceptibility to **corrosion** depends upon their composition.

The most vulnerable aspects of iron and steel structures are often their **connections** where stresses are generally highest, especially at holes for fasteners.

Protection against corrosion of iron and steel requires first the elimination of rust from the surfaces (by sand-blasting, etc.) and then painting the surface with an appropriate product.





Malvasia Bridge, Venice, 1853 – cast iron









Repair of ferrous metal structures: research







lamellar cast iron

ductile cast iron

• aluminium alloy

stainless steel

carbon fibres

5000

coatings Original cast iron



Bending tests before and after repair Strengthened area



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





General principles for existing buildings in Italian seismic code

- Upgrading: necessary when add
 - adding storeys,
 - changing use of the building with consequent increase of loads >20%,
 - substantially changing the building shape
 - substantially changing the building structural behaviour

Improvement: possible when

- acting on single structural elements
- acting on monumental buildings

The obligatoriety of **safety evaluation for upgrading intervention** and the necessity of some kind of **evaluation for the improvements** is stated.

The **degree of uncertainty which affects the safety evaluations** of existing buildings and the design of the interventions is taken into account through the use of **confidence factors**: in fact the use of methods of analysis and assessment depends on the completeness and reliability of available information.



Example of seismic improvement: cultural heritage building



Macroelement	Capacity (g) before the intervention	Capacity (g) after the intervention	Increase %	Seismic demand (g) defined by the code	Capacity / Demand (%) after the intervention
Façade F1	0,083	0,138	66%	0,273	51%
Façade F2	0,158	0,195	23%	0,280	70%
Upper façade F1	0,322	0,536	67%	0,375	143%
Apse A1	0,223	0,362	62%	0,289	125%
Apse A2	0,158	0,281	79%	0,277	101%



Example of seismic improvement: the church of S. Maria del Pianto



XVIII Century church by Frigimelica with central plan and some irregularities due to following resets done in the first half of the XX Century



Critical survey





Example of seismic improvement: the church of S. Maria del Pianto



From the analyses carried out, it was pointed out that the most vulnerable element is the **façade**, in case of **overturning with partial involvement of the lateral walls**.

This is also a possible mechanism, due to the presence of corresponding **crack pattern** close by the façade.





Example of seismic improvement: the church of S. Maria del Pianto

Collapse coefficients in the previous state (orange) and simulating **bracings** (green), installed between 2003 and 2004 on the roof above the façade. This has significantly **improved the seismic response of the façade**, as shown by the increase of the collapse coefficient for the overturning.







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 **seismic risk assessment**, the criteria for the design of **intervention**, according to the New Italian Seismic Code, but adapted to the needs of cultural heritage masonry buildings.

For those buildings it is not required an upgrading to current seismic protection level, but 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.



Italian Guidelines – § 2 – Safety and conservation requirements

Procedure for the seismic safety assessment

- definition of the seismic action;
- definition of an aseismic protection level;
- obtain an appropriate knowledge of the building and define a correct confidence factor;
- definition of one or more mechanical models of the structure or of some parts of the structure (macro-elements) and use of one or more analysis methods;
- evaluation of safety indexes obtained considering the PGA corresponding to every limit state before and after a compatible intervention of improvement and (quantitative and qualitative) comparison of the reached protection level with the seismic risk and with the use of the building.
- use of appropriate detail rules for the realisation of the interventions (compatibility, durability...).



The seismic upgrading is not compulsory: what is required is a comparison between the current safety level and the safety level after the intervention, adopting a protection level (γ_1 factor) that varies according to the relevance and the use of the building, and that is used to reduce or increase the reference seismic action.

The criteria for the intervention are the same already mentioned, but specific attention has to be paid to **conservation principles**. Besides, a clear understanding of the structural history of the building (type of action, causes of damage, etc.) should set its mark on the design.



Renaissance walls in Padova - Italy





Intervention should not only be aimed at reaching appropriate **safety level of construction**, but they should also guarantee:

Compability and durability Integration or support to existing assessed behaviour Correct typological behaviour of the building Use of non-invasive techniques If possible, reversibility or removeability Minimization of intervention









The damage obtained during the **Umbria-Marche earthquake** in 1997 on buildings retrofitted after the 1979 earthquake, together with experimental and theoretical studies carried out, pointed out problems related to **poor masonry quality** but also underlined the limits of some **badly executed strengthening intervention techniques** which became very popular and even compulsory according the previous seismic code: they in fact frequently showed scarce performances (injections, jacketing) or even worsened the local/global structural behaviour of existing masonry buildings (jacketing, replacement of flexible floors with stiff floors).









Building strengthened after the Bovec earthquake (Slovenia) in 1998, damaged again during the 12/07/2004 earthquake



The execution of interventions that locally change the stiffness of the structure has to be adequately evaluated. The **renovation of flexible floors into stiff floors** cause a different distribution of seismic actions that can be favourable/unfavourable and has to be taken into account into the modelling and analysis phases.

It was abandoned the idea that it is possible to confer to each structure a "box" behaviour, by means of indiscriminate "a priori" interventions, considering that, for example, a stiff R.C. floor is not crucial for the safety of a masonry ordinary building.



Some effects of the introduction of R.C. elements in masonry existing buildings







The orthogonal walls are not adequately connected each other and to the new R.C. slabs



The experience of the Umbria-Marche earthquake showed the effect of stiffening the horizontal diaphragm by **substituting original wooden floors with stiff reinforced concrete floors**: traditional techniques, aimed only at reducing excessive deformability of the floors, are now proposed.



Sliding of the roof floor: the masonry is not adequately strengthened

Expulsion of the façade: the tie-beam is supported only by the internal leaf of a multi-leafs masonry: load eccentricity and reduction of the resisting area





Reinforced injection: - highly invasive

- scarce performances
- adhesion problems















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General requirements for interventions:

- 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 guidelines analyse the following **types of interventions**, giving useful indications for the conception and the design of the intervention:



In the following slides some, **examples of improving and strengthening interventions** realised according with the indications of the guidelines are showed.



Interventions to improve the connections (walls – floors)

The goal is to allow the structure to manifest a **satisfactory global behaviour**, by improving the connections between masonry walls and between these and floors: this may be achieved via the **insertion of ties, confining rings and tie-beams**.

An effective connection between floors and walls is useful since it allows a **better load redistribution** between the different walls and exerts a restraining action towards the walls' overturning. Considering wooden floors, a satisfactory connection is provided by fasteners anchored on the external face of the wall





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Interventions to improve the connections (walls – floors)

- Anchoring ties
- Reinforcing rings
- Floor/walls connections





Residential buildings, Montesanto (Sellano)





states to their affriencials faits in by



Interventions to improve the connections (walls – floors)



Orologio Tower, Padova











Vanga Tower, Trento











Interventions to improve the connections (walls – floors)



S. Stefano Church, Monselice













Application of composite materials









Reinforcement materials: CFRP, SRP, SRG, BTRM







Results

	Emax	δ _{max}	Emax/ FVM	$\delta_{max} / \delta_{VM}$
	[<u>kN</u>]	[mm]	-	-
VM	1,40	16,79	-	-
VM-SRG	13,55	50,12	9,70	2,99
VC_SRG	15,45	70,06	11,06	4,17
VC_BTRM	12,08	24,14	8,65	1,44
VC_SRP	24,82	26,87	17,78	1,60
VC_CFRP	12,93	30,22	9,26	1,80

















Caracterization of reinforcement materials





Application of FRP laminates to vaults: examples





S. Fermo Church, Verona









540 510 480 450 420 390 360 330 300 270 240 210 180 150 120 90 60 30 Ascisse arco (cm)







Sandro Gallo Bridge, Venezia





Application of extrados elements and FRP laminates to vaults: examples



Ducale Palace, Urbino:

- Substitution of the thin "frenelli" (5 cm thick) with solid brick panels (16 cm thick).
- Application to the both sides of CFRP strips to make active the "frenelli" up to their ends.
- Realization of transverse ribs connected to the "frenelli" edges by thin solid brick panels and a CFRP strip on the top.









Interventions aimed at the **in-plane stiffening of existing floors** must be carefully evaluated since the horizontal seismic action is transferred to the different masonry walls in function of the floor plane action, depending on its stiffness.

In plane and flexural floors stiffening with 'dry' techniques is obtained by providing, at the extrados of the existing floor, a further layer composed by **wooden planks**, with orthogonal direction respect the existing.



The use of metallic belts or FRP strips, disposed in a crossed pattern and fixed at the extrados of the wooden floor or the use of metallic tiebeams bracings, may improve the stiffening effect.































8,606

2,668

2,283

1,59

1,55

Interventions to reduce excessive floor deformability





Natural fibres composites (NFRP) applied to timber elements: local bond aspects, in-plane stiffening of floors







Local bond aspects






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Interventions to reduce excessive floor deformability







Interventions on the roof structures



Ducale Palace, Urbino









Interventions on the roof structures



Arsenale, Venice, XII c.















25













Interventions aimed at increasing the masonry strength may be used to **re-establish the original mechanical properties** lost because of material decay or to **upgrade the masonry performance**. Techniques used must employ materials with mechanical and chemical-physical properties similar to the original materials.

Interventions should be **uniformly distributed** (both strength and stiffness).

With opportune cautiousness, suggested techniques are the "scucicuci", non cement-based mortar grouting, mortar repointing, insertion of "diatoni" (masonry units disposed in a orthogonal direction respect the wall's plane) or small size tie beams across the wall, with connective function between the wall's leaves.



Mortar repointing

Injections technique: example of suitable execution and of

problems related to uncorrected execution (e.g. lack of uniformity)



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Interventions to strengthen the masonry walls

- □ Injections;
- □ tying;
- □ combination of techniques;
- □ bed joints repointing
- □ bed joints reinforcement
- □ jacketing;
- □ "scuci-cuci";
- □ application of FRP materials.



INTONACO NON DISTACCATO DAL SUPPORTO CHE GARANTISCE LA TENUTA ALL'ACQUA









Grout injections research: grout selection through laboratory tests







Injectability

Grout injections research: injection on multi-leaf stone walls and calibration of models



 $f_{wc,0} = (V_{ex}/V)\Theta_{ex}f_{ex,k} + (V_{inf}/V)\Theta_{inf}f_{inf,0}$







Application of transversal elements and ties to walls research: stone masonry wall



- Improvement in the strength of the wall
- Reduction of the dilatancy of the walls











Shaking table tests on Out-of-Plane behaviour of single structural elements

Strengthened by:

- Injections
- Steel ties
- Both; injections + steel ties











Shaking table tests on Out-of-Plane behaviour of single structural elements

- Failure mechanisms;
- Variation of dynamic characteristics (frequencies, mode shapes);





Effect of six injection grouts, use to strengthen irregular stone masonry walls, damaged by April 6th 2009 earthquake

- Diagonal compression test;
- Characterization of grout-original mortar interface.







Effect of six injection grouts, use to strengthen irregular stone masonry walls, damaged by April 6th 2009 earthquake







Dynamic behaviour whole structures Building Models

Floor Dimensions:
2.40m x 2.8mMasonry deepness: 0.33m
(12cm external layers 9cm internal filler)Height: 3.60mDouble planking wooden floorsRegular openingsAdditional masses (500kg per floor)



Montenegro earthquake (14/4/1979) was chosen and the signal was elaborated considering the scale factor of 2:3;











The dynamic behaviour of models was monitored using several systems simultaneously:

Accelerations were	 16 Sensors fixed 	Experimental steps		
recorded using two	externally at masonry;	URM Model	SM Model	RM Model
Systems.	6 Sensors fixed	0.05g XY	0.05g XY	0.05g XY
5	internally to the wooden	0.10g XY	0.10g XY	0.10g XY
13 14 9	beams;	0.15g XY	0.15g XY	0.15g XY
	and the second	0.20g XY	0.20g XY	0.20g XY
3		0.25gI XY	0.25g XY	0.25g XY
11 12		0.25gII XY	0.30g XY	0.30g XY
7 4		0.30g XY	0.35g XY	0.35g XY
8 1	No and A and a set	0.35g XY	0.40g XY	0.40g XY
2	- Contraction and a second	0.40g XY	0.45g XY	0.45g XY
Y	00 0 0 0 0 0 0 0	0.45g XY	0.50g XY	0.50g XY
Displacement monitoring		-	0.55g XY	0.55g XY
systems:		-	0.55g X	0.55g XY
More than 100 points		-	0.60g X	0.60g XY
were optically monitored:		-	0.65g X	-
Deformation of 2 nanala:		-	0.70g I X	-
		-	0.70g II X	-

• Base Displacement;



Two identification methods: **FDD** (*Frequency Domain*)

SSI (Time Domain)





Town Walls, Cittadella:

- local rebuilding
- grout injection
- repointing









Grout injections: other applications

Castle of Este (Padova, XIV c.)

- local rebuilding
- metallic ties
- injections
- tie-beam at the top of the walls



S. Giustina Monastery Bell

Tower (Padova, XIII-XVII c.):

- steel ties and frame
- local rebuilding
- injections
- reinforced repointing





Reinforced repointing experimental researching and modeling: the use of steel bars



Resin FIP C

or S FIP 180

700

Aesthetic sealing





Monotonic compression tests:

- steel bars reinforcement (2Ø6mm)
- repointing material:
- hydraulic lime mortar
- synthetic resins (2 types)
- •one side strengthening





Reinforced repointing experimental researching and modeling: the use of steel bars



- no improvement in the strength of the wall
- reduced dilation of the repaired panels against the not consolidated ones
- · reduced dilation of the consolidated faces of the repaired panels
- reduced cracking pattern on the repaired faces against the not repaired one
- reduction of the tensile stresses in the bricks (40%) and absorption by the bars



Reinforced repointing experimental researching and modeling: the use of steel bars

Creep tests:

- Steel bars reinforcement (2Ø6mm)
- Repointing mortars:
- polymeric hydraulic lime
- hydrated lime and pozzolana
- Two sides strengthening with different configurations











Reinforced repointing experimental researching and modeling: the use of steel bars







- Diffused cracking pattern
- Reduction of the dilatancy of the walls
- Tertiary creep condition in the strengthened panels achieved for deformations over 70% higher than the original ones



Reinforced repointing testing and modeling: the use of FRP bars and thin strips







Using innovative materials while ensuring compatibility and removability









Reinforced repointing: application for the control of long term behavior

S. Sofia Church, Padova, XII c.









Reinforced repointing: application for the control of long term behavior



The Civic tower of Vicenza, XII-XV c.:

Slender structure with a base section of 6.2x6.5 m and a height of about 82 m, the Tower suffers a substantial out-ofplumb, and a damage characterized by localized deep cracks, diffused micro-cracks and material deterioration

The interventions:

• grout injections;

Crack

- pointing of mortar joints;
- reinforced repointing;
- · metallic horizontal reinforcing rings and anchoring ties.











Reinforced repointing: application for the control of long term behavior

The bell tower of the Cathedral of Monza (XVI c.):

- 70 m tall
- passing-through large vertical cracks on some weak portions of the West and East sides (slowly but continuously opening since 1927)
- wide cracks in the corners of the tower up top 30m
- damaged zone at a height of 11 to 25 m with a multitude of very thin and diffused vertical cracks
- in the heaviest portions of the wall the current state of stress is close to the 70% of the masonry compression strength





Reinforced repointing: application for the control of long term behavior











Diffused strengthening interventions design:

- Injections
- "Scuci-Cuci"
- Bed joints reinforcement
- Placement of reinforcing metal rings reinforcing tie-rings at different levels
- Strengthening of the corners



Diffused strengthening interventions execution:

- Injections
- "Scuci-Cuci"
- Bed joints reinforcement
- Placement of reinforcing metal rings reinforcing tie-rings at different levels
- Strengthening of the corners













Application of FRP laminates to walls research: brick masonry wall specimens











Investigations on FRP-to-clay bricks bond in the case of normal forces Correlations among mechanical properties of solid clay bricks

Three-point flexion





Pull-off test











Investigations on FRP bond to clay bricks and masonry prisms





Four types of fibres (carbon, glass, basalt and steel);

Two setups: Single and Double-lap.

Characterisation of materials

□ test design and execution

test analysis

(within the framework of the RILEM Technical Committee TC 223-MSC)







Investigations on FRP bond to clay bricks and masonry prisms



Four types of fibres (carbon, glass, basalt and steel);

different anchorage lengths.

□ Characterisation of materials

 $\hfill\square$ test design and execution

test analysis





Interventions to strengthen the masonry walls Investigations on FRP-to-clay bricks bond in the case of mixed actions





Results

Specimen	brick type	loading path
Vp01	S4 - facing	monotonic (A)
Vp02	S3 - extruded	cyclic (A)
Vp03	S3 - extruded	cyclic (A)
Vp04	S4 - facing	cyclic (A)
Vp05	S4 - facing	monotonic (A)
Vp06	S4 - facing	cyclic (A)
Vp07	S3 - extruded	cyclic (B)
Vp08	S3 - extruded	cyclic (B)
Vp09	S3 - extruded	monotonic (B)
Vp10	S3 - extruded	cyclic (B)
Vp11	S4 - facing	cyclic (B)
Vp12	S5 - extruded	monotonic (B)
Vp13	S2 - facing	monotonic (C)
Vp14	S2 - facing	cyclic (C)





Test design and performing





Interventions on the foundation structures





Town Walls, Cittadella



Interventions on the foundation structures





Repair mortar system for reinforced concrete elements

- Rehabilitation of reinforced concrete axially loaded elements with polymer-modified cementicious mortar
- Efficiency of rc beams repaired with polymermodified cementicious mortars
- Flexural capacity of rc beams repaired with steel reinforced grout (srg)
- Shear bond testing of concrete repairs









Repair mortar system for reinforced concrete elements

Efficiency of RC beams repaired with polymer-modified cementocious mortars

- increase the value loads that induce the first crack (14% to 44%);
- the position of the repair had greater influence on the beam behaviour;
- re-established the same stiffness of the nondamaged control beams.





Load-deflection A-type beams


- Rehabilitation of reinforced concrete axially loaded elements with polymer-modified cementicious mortar
- this study confirmed that it is necessary to employ mortars with elastic modulus at least similar or equal to that of the concrete substrate and preferably higher compressive strength;
- when repair mortar is applied on all four sides is possible to eliminate o reduce debonding effects









Repair mortar system for reinforced concrete elements Shear bond testing of concrete repairs

- 3 samples for each type of combination concrete/repair mortar;
- creation of a notch at the interface concrete/repair layer;
- 3 level of precompression: 0.05 MPa 0.15 MPa 0.45 Mpa;
- shear applied in displacement control;
- actually data elaboration is in progress.

The notch





Test setup



Instruments



Interface after sample failure

- two storey structure
- reinforced concrete frame structure
- it consists of three sectors: A, B, and C



Trap shooting building, Venice









Trap shooting building, Venice



Structural joint and rotation of columns



Crack at the midspan of a beam



Typology of infill



Foundation detail



Industrial buildings in L'Aquila – Pile industrial area



Lack of covering associated to corrosion



RC reticular beams - Roof body $\boldsymbol{\zeta}$



Damage in the infills



Metallic roof - body λ



Damage concentrated in the zone of casting discontinuity



Introduction of seismic isolation and application to monuments



SEISMIC ACTION

Seismic isolation of the Statue of Nettuno & Scilla in Messina (Sicily): particular of the support with **isolator and SMAD device**.





Introduction of seismic isolation and application to monuments





Examples of real cases of intervention on historical constructions (I): Limiting the interventions by using investigations and monitoring the timber roof of the Palazzo della Ragione – Padova



The roof covers a unique, skewed room, approximately 28 m wide and 80 m long.

The roof is formed by slender ribs (36x40 cm²), obtained by joining curved boards 12 cm thick, whose length varies from less than one meter to three meters.





Decay survey

Preliminary design hypotheses assumed that only a complete dismounting could have permitted a "safe" repairing of heavily deteriorated zones of the ribs of such a "delicate audacious" structure, being conscious however that this solution could have caused unacceptable losses of the existing material and components and, in general, of its original character.





Deterioration of the ribs detected: 1. in the end sections 2. in the joints

3. in the lead joints

Deterioration of the joists (4)











Investigation and monitoring

Two different types of investigation were used for the analysis of static and dynamic effects of wind:

- in situ measurements of wind pressure on selected points
- wind tunnel tests on a reduced scale model of the building and of significant surrounding part of the historical center of the town



position of the wind pressure transducers on the external surface of the roof

A monitoring system of some **relevant cracks** was placed: the seasonal changes were evident.







Investigation and monitoring



Palazzo della Ragione WebMonitoring

Web monitoring home page

Comparison of the results of the

dynamic tests with the 3D FE

modeling of the roof

Idea:

- wind effects monitoring
- stepped sine test
- FE modeling
- modal identification
- www data management

www database



The results of the **investigations**, combined with appropriate **structural analyses** (calibrated with the test results), allowed to design the intervention being much more confident on the "robustness" of the structure, providing **full 3D behaviour**, and the essential contribution given to the stability by the "shell" formed by the nailed boards, would be in any phase maintained.



Investigation and monitoring

Wind tunnel tests on a reduced scale model of the building and of significant surrounding part of the historical center of the town was used to confirm the analysis of static and dynamic effects of wind.



reduced scale model for wind tunnel tests



Repair intervention

The design of the **local repairing** was made by taking **simple temporary measures** allowing for maintaining the stable 3D behavior and inhibiting local buckling in any phase of the works, by simply limiting the removal (when needed) of the boards forming the shell very locally, in order to permit local repairing, and through simple lateral supports.



NIKER WORKSHOP ACRE, ISRAEL 17.12.2012







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- Teaching for Architectural Engineers (MsC European agreement)
- Different academic courses concerning structural safety of monuments and historical buildings (e.g. Restoration – Structural Problems of Monuments and Historical Constructions)



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THANK YOU FOR YOUR KIND ATTENTION



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