Deliverable 10.5

Integrated methodology for effective protection and earthquake improvement of cultural heritage

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WORKPACKAGE 10: Guidelines for end-users

Leader: ITAM

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Small or medium scale focused research project
THEME: Environment (including Climate Change)



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1 INTRODUCTION

1.1 DESCRIPTION AND OBJECTIVES OF THE WORK PACKAGE

The exploitation of NIKER results covers both the use of exploitable knowledge and exploitable measures and products. Exploitable knowledge brings mainly non-commercial benefits for project participants and beyond the partnership (e.g. cultural heritage institutions, owners, RTD performers). By means of guidelines prepared in WP10, disseminated as described previously in other deliverables, the internal processes are improved for authorities in charge of CH maintenance. In such a way, cultural institutions and owners of cultural heritage can integrate the technologies and methodologies developed into their project and will be able to carry them out more effectively and more efficiently. The WP10 is subdivided into:

WP10.1: Guidelines for specific problems. These guidelines outline the main results obtained in WP3; WP4; WP5; WP6, WP7 and WP8 and are intended for designers and users of the technologies. Therefore, the entire work carried out into the project will be substantially simplified for the needs of the end-users and designers, by providing simple design rules, design formulations and design charts.

WP10.2: Guidelines for integrated methodologies. These guidelines summarize the main results obtained in WP7; WP8 and WP9 and are mainly oriented to designers or bodies responsible of the management and maintenance of the structures. They will contain the description of the new integrated knowledge based approaches for the protection of the CH from earthquake-induced risks emerging from the project.

The main objectives of WP10 can be summarised as follows:

- Produce guidelines for the direct end-users of the developed technologies and tools (designers, architects, engineers, construction companies, bodies responsible of building maintenance, etc), with practical information on design of interventions, execution of techniques, assessment tools, monitoring procedures;
- Produce guidelines for production and installation of advanced instrumented dissipative devices;
- Produce guidelines for owners and end-users of the developed technologies and tools (public entities, bodies responsible of building maintenance, authorities, etc), with description of step-by-step integrated methodology for effective protection of cultural heritage;
- Spread awareness and establish reliable, effective, compatible, integrated approaches for the protection of cultural heritage from earthquake-induced risks.

The outcome of Workpackage 10 is presented in 5 deliverables, covering the aspects listed above.

1.2 SUMMARY AND OBJECTIVES OF THE DELIVERABLE

The guidelines concerning the integrated methodology for effective protection and earthquake improvement of cultural heritage (D10.5) contain the description of the entire approach, based on a combination of both already available methods, developed and quantitatively characterized in the framework of the project, as well as newly proposed technologies for intervention, assessment, monitoring (demonstration of the overall methodology on real case-studies in WP9), and refer to the documents D10.1, D10.2, D10.3 which provide feasible solutions to specific problems. The main objective is to implement an integrated methodology for effective protection of CH assets from earthquake, including the main steps of all the above mentioned phases, for management and planning of preservation measures.

2 PROTECTION OF CULTURAL HERITAGE

Although a comprehensive knowledge concerning the nature of earthquakes has been achieved, it is so far unmanageable to foresee with confidence either the time or the intensity of their occurrence. As a consequence, in the context of cultural heritage protection, professionals´ room for manoeuvre remains limited to those measures which attempt to improve the seismic performance of constructions and to adequately repair earthquake-induced damages. Improving the seismic performance of historic buildings should be integrated into a regular maintenance program, based on periodic inspections by purposely trained architects and engineers. Administrators in seismic zones should ensure that these inspections are carried out and that a full inventory with detailed documentation is prepared before the next earthquake.

The actions needed to prepare seismic safety plans for historic buildings are:

- Estimate seismic hazards in terms of the expected occurrence of earthquakes of various intensities and their return period.
- Estimate seismic risk (loss of life, material damage, functional loss, building degradation).
- Identify structural systems and models for analysis for historic constructions. Prepare record drawings and seismic survey forms.
- Evaluate structural responses to earthquakes of various intensities.
- Determine type and degree of damage for different predicted seismic intensities.
- Develop alternative upgrading (improvement/strengthening) methods and estimate costs, defining the required safety level for the construction and applying conservation ethics to determine the minimum intervention necessary.
- Develop plan schedules and give approximate estimates of cost of alternative schemes for different return periods.
- Prepare a management plan for a chosen scheme. Obtain budget allocations based on accurate estimates. Execute desirable works to increase seismic resistance.

Furthermore, for a correct management of heritage structures the following should be also considered:

- *Regular inspection of architectural heritage.* It aims at discovering structural weakness or potential critical problems, which must be clearly translated into understandable information and transmitted to the relevant stakeholders and decision makers, namely cultural heritage owners, managers, users, public and especially local and regional authorities together with suggestions concerning protection strategies and measures. Such recommendations need to involve estimated costs of necessary interventions and identification of time schedule priorities.
- *Regular maintenance.* The defects or deficiencies that are discovered by regular inspection must be repaired or rectified as soon as possible. In case of lack of funding, it is recommended to perform even temporary measures that may safeguard lives and cultural heritage assets. Maintenance measures, in general, do not require design work or engineering supervision. In some cases these can usually be left to the skills of properly trained craftsmen. A maintenance guide is in any case a useful tool, and should combine tips for inspection with recommendations on how to fix problems that are identified.

Efficient preventive measures cannot be materialized without creation of appropriate incentives and regulations. Ideal legislative tools should aim at i) improving the structural condition of the stock at risk on the basis of regular qualified inspections, and early repair of deficiencies that are identified ii) regular maintenance supported by maintenance plans and maintenance manuals, iii) implementing feasible and affordable structural measures and iv) employing well-trained and skilled craftsmen to implement typical, tested solutions. Education and training in relation to cultural heritage must be focused on raising awareness and promoting regular coordinated training of rescue teams and enhancing controlling systems.

2.1 GENERAL APPROACH

Past experiences exposed the urgency to re-think the methodological and technical approaches to seismic vulnerability of historic buildings, on the grounds of the considerable adverse impact induced by the inadequacy of preventive measures applied in the past, often too intrusive, cost-inefficient, and unreliable. These guidelines propose a new integrated methodology which establishes a wider, multi-disciplinary framework of activities, including essential steps complementary to the actual execution of interventions.

In the context of such integrated methodology it is important to recall the necessity for any action performed on historical structures to comply with recognized conservation principles. These principles are stated in international documents ICOMOS / ISCARSAH Recommendations for the Analysis and Restoration of Architectural Heritage, (ICOMOS/ ISCARSAH, 2005), and the Annex on Heritage Structures of ISO/FDIS 13822, (ISO/TC96/SC2, 2010). Among the most important it is possible to mention:

- Respect for structural authenticity.
- Structural reliability requirements.
- Minimal intervention.
- Compatibility.
- Durability.
- Non-intrusiveness (non-invasiveness).
- Non-obtrusiveness.
- Removability.

It is recognized that complying with all these criteria may be impossible in some cases, and some prioritization or choice, based on engineering judgment, is often necessary. Trying to satisfy these conditions will assist in conceiving and designing both efficient and respectful interventions consistent with conservation principles. The necessity of prioritization highlights, therefore, the ambiguity which often governs the field of cultural heritage protection and that usually translates into a difficulty for practitioners to make decisions.

The main objective of these guidelines is indeed to outline the procedure required to support and control an adequate decision making process, aimed at the selection of correct intervention to be performed.

3 INTEGRATED METHODOLOGY

For the study and intervention on a heritage building it is proposed to distinguish between the phases defined below. Monitoring has been considered as a relevant tool in all these phases and is applied, alongside with inspection and structural analysis, in all of them. It is also proposed to update the structural models, throughout all the phases, to take into account the changes introduced (such as the effect of the strengthening) and the variations detected by means of monitoring. If significant variations are observed, a new seismic assessment should be carried out using the updated models in order to analyze the meaningfulness of such variations and their implications for the seismic capacity.

The different phases considered are:

1. **Investigation phase**, oriented to gather all the needed data to obtain the necessary information on the condition and load carrying capacity of the structure and to conclude on the repair, stabilization or strengthening needs. This phase involves all the operations concerning inspection, diagnosis and safety evaluation.

2. **Intervention phase**. It includes the operations leading to the full design of the intervention and its practical implementation. In particular, it may include incremental approaches based on step-by-step procedures.

3. **Evaluation phase**. Beginning after (or even during) the execution of the intervention and elapsing during a limited and defined period of time. During this phase the intervened structure is continuously or periodically (but frequently) assessed and the efficiency of the intervention is evaluated through a specific inspection and monitoring program. The phase normally encompasses a short period of time (from months to up to 2- 4 years) and is oriented to the evaluation of the intervention through intensive survey.

4. **Management phase.** Its purpose is to control the response of the intervened structure and the maintenance of the expected efficiency of the seismic upgrading solution. The response of the structure is continuously or periodically surveyed. One of the aims of this survey is in detecting unexpected responses that may alert of possible problems. It starts after the evaluation phase and lasts up to the end of the maintenance period (period of time during which the intervention is expected to keep sufficiently efficient, with limited maintenance works). If needed, improvements or corrections are undertaken to secure the required efficiency levels.

In spite of the distinction between the different phases, they are intimately connected and any general action on a historical structure should plan all of them according to unified approaches and criteria. Ideally, similar experimental and numerical tools should be utilized in all the phases, and an adequate and balanced technical and budgetary effort should be devoted to all of them. However, it is also recognized that different problems (regarding the condition of the building, the seismicity, the structural technology and economical or technical constrains) may lead to combine the phases in different ways or to assign them a different relative weights.

3.1 INVESTIGATION PHASE

This phase is aimed at characterizing the condition of the building, its structural reliability and the intervention needs. More specifically, it involves a detailed inspection of the building, a diagnosis on the ultimate causes of damage and deformation, the structural verification (including seismic assessment) and the identification of the need for stabilization, repair or upgrading. The investigation phase aims at identifying the active deterioration processes, the overall deformation trends, the dynamic properties and response of the structure and the need for emergency actions. A preliminary step might involve a research of the history of the construction and particularly the responses to significant seismic events throughout time. This task can help suggesting the failure mechanisms which are characteristics of the construction providing therefore clues for the subsequent investigation actions to be performed. Structural, geometrical and critical surveys of the building should be considered in this preliminary phase. Following the gathering of historical information, inspection is carried out to provide all the data needed for a characterization of the building regarding geometry, construction features, materials, morphology and damage. This information is used for two different purposes: (1) the preparation of the numerical model input data and (2) the design of the monitoring. Inspection comprises visual inspection, different NDT and MDT and in-situ or laboratory tests (chemical, physical or mechanical) oriented to identify the material composition, existing alterations, working stress levels, material properties, soil foundation properties and damage distribution, among other aspects. In turn, an initial structural analysis may assist in taking decisions on the type of monitoring to be implemented (type, accuracy and range of sensors, number of measurements and critical locations). It is advisable to refer to D10.4 for details concerning the recommended investigation strategies to be carried out on site.

In addition, in the case of lack of backing information provided by codes or relevant research literature, laboratory assessment of structural connections can be considered as a complementary part of the investigation process. Testing strategies endorse determining the capacity of a connection undergoing horizontal loading; unfortunately, only small samples can be taken from existing buildings or, in a majority of cases, they can just be reproductions of existing structures. Either way, if correct assumptions are made and a robust testing protocol is implemented, precious information on structural capacity can be derived. However, it is crucial that tests are performed to a standard that allows quantifying all the parameters that control the performance of the connection, as these can then feed into appropriate analytical and computational models and constitute the terms for comparison in case one decides to proceed to the strengthening. In order to provide end users with such standards, D10.2 describes a set of procedures that can be used for the characterisation of structural connections, detailing set-up, samples, instrumentation and loading procedure.

3.2 Intervention phase

The research carried out during the previous phase should permit conclusions on the performance of the building and the need for a possible seismic upgrading. The need for this seismic upgrading may be required in order to avoid inacceptable risks to people, to prevent damage to valuable artistic contents, or to limit the damage experienced by the heritage structure itself.

As suggested by the ICOMOS/ISCARSAH Recommendations (2005), an incremental approach can be adopted during the execution of the definitive intervention. Monitoring the response of the structure as interventions progress, it is possible to have an actual quantitative image of their effect. This can be especially relevant in cases of fund shortage, in which event the execution of parts of the intervention may be postponed or cancelled in case they are proven to be unnecessary. In the case where provisional or emergency measures have been taken, usually an incremental strategy can also be adopted before reaching a conclusion on the final intervention plan. This method allows for a more considered study of the structure to be carried out using monitoring and structural analysis, in a data or model driven approach respectively, or both.

The typology, geometry and implementation strategy of the strengthening system should be chosen so as to effectively address structural problems and, at the same time, to respect the principles outlined in section 2.1. A number of factors come into play in this decision-making process; for instance, one should consider the applicability of a strengthening technique to a specific case study as well as the advantages and disadvantages of various systems in respect to the on-site constraints. Besides the logistic issues, the optimized design and successful application of a strengthening system will also largely depend on the designers' capacity to fully understand how the system will behave, what parameters control its performance, how these can be determined, and how they should be implemented in an analytical model to predict the response of the structure in the strengthened set-up.

In light of these considerations, D10.1, 2 and 3 aim to support end users before and during the design of the intervention by providing concise data useful for the decision process. In the specific, it is recommended to refer to: D10.1 for details concerning design and execution of interventions on vertical and horizontal elements; D10.2 for an overview of a number of standard strengthening systems of connections is provided: applicability, advantages and disadvantages, and optimum installation procedures are summarised. Finally, guidelines for deriving performance parameters from tests and design codes are given and design procedures suggested; D10.3 for a summary of the various aspects related to the use of innovative devices for the strengthening of structural connections. Innovative devices have been developed and refined during the project in response to the recommendations of current structural codes, which encourage the increase of ductility and energy dissipation to ensure better seismic performance of structures. A summary of information such as applicability, positive effects on the overall structural system, pros and cons and so forth is given in D10.3, thus providing end-users with all the elements to decide in favour or against the application of these techniques during intervention. Furthermore, D10.3 supplies information regarding the possible use of instrumented strengthening elements to the purpose of jointly applying strengthening, monitoring the evolution of damage and provide early warning. In addition, the NIKER Catalogue (D3.6), available online at www.niker.eu, defines the main design parameters and requirements for materials and intervention techniques, including those described in the above mentioned D10.1, 2 and 3, and help in a reasoned choice of interventions by linking them to possible failure mechanisms, construction typologies and materials.

The intervention should be designed for a clearly stated period of time (the maintenance period, as defined in section 2) during which it is expected to keep sufficiently efficient with limited maintenance works. The completion of the design period signals the point at which new assessment works should be undertaken, eventually leading to the improvement or replacement of the existing intervention.

3.3 EVALUATION PHASE

After the full execution of the intervention, a subsequent monitoring phase is proposed, extended to a limited period of time, during which the upgrading solutions are carefully evaluated. The evaluation period is oriented to control the correct implementation of the upgrading solutions and to verify that the expected improvement has been actually achieved. The response of the strengthened structure is analyzed and the performance of the strengthening solutions is carefully investigated regarding their efficiency and actual influence on the response of the structure.

The strategies to be utilized during this phase are similar to those proposed for the investigation and intervention phase; however, their use is extended to a longer period allowing for an appreciation of the variation (or maintenance) of the upgrading effect on the structure. For details it is recommended to refer to D10.4.

The duration of the evaluation phase may involve variable periods from a few weeks or months to even one or more years, depending of the nature of the problem, the importance of the building and the strategies applied.

3.4 MANAGEMENT PHASE

The adequate performance of the strengthened structure and the strengthening methods and devices is subjected to a long term survey for verification purposes and, if necessary, to ensure their adequate condition and performance. This management phase extends up to the end of the maintenance period (see section 2.1). As mentioned, the maintenance period sets up the time during which the upgrading solutions are supposed to keep sufficiently efficient and in satisfactory condition with only (and adequately planned) maintenance works. The attainment of the end of the maintenance period should motivate new studies and a possible substitution or improvement of the intervention.

The capabilities for verification and quality control of the structure following the intervention are heavily affected by the available budget. Nevertheless, a minimum degree of verification should be established in any case. Generally, the control programme should cover the entire design period in order to assess the efficiency of the intervention up to its full completion, at which point a new assessment and possible new interventions might be needed. However, two different control phases, characterized by a different intensity, can be considered.

1. The first phase may encompass a short period and is oriented to the evaluation of the intervention through a more intensive survey (see section 3.3). For example, yearly inspection of damaged, repaired and strengthened elements may be performed for a period up to 2 - 4 years.

2. A second period of less intensive, but sufficient controlling activity must be extended to the entire maintenance period. The aim of this second phase is at continuously, or periodically, verifying the maintenance of the efficiency of the upgrading solution and detecting unexpected responses that may alert of possible problems. During this second phase, the post-intervention programme should also include a detailed inspection and maintenance plan.

During both phases, standard inspection techniques can be complemented by NDTs performed on repaired and strengthened elements. These inspections should be performed periodically according to a long term plan and conclude with a definitive evaluation at the end of a certain time frame.

Also during both phases, monitoring or inspection may point to the need for corrections or additional improvements. To the possible extent, the intervention project should include possible criteria for decision taking and the possible improvement of the strengthening devices or solutions implemented. As already mentioned, the strengthening technologies must allow for possible improvements or corrections and solutions not actually acceptable should be disregarded. Early warning systems, discussed in the following section, may be or large application during these post-intervention phases.

Comparison of ambient vibration tests at pre- and post-intervention stages can provide a global estimation of the effect of the interventions. Local and global monitoring systems should act in complementary fashion. In the cases where the decision of no intervention was taken, monitoring may be used as a means of verification and control of that decision.

The post-intervention programme should also include a protocol for actions to be undertaken in the case of new seismic tremor. The development of a new structural inspection campaign may be then carried out immediately after it, giving place to a re- consideration of the entire assessment and intervention on the basis of the information provided by the new observational and monitoring results.

Recommended verification and control strategies are outlined in D10.4.

4 SELECTION AND INTEGRATION OF INTERVENTIONS

Selecting and integrating feasible intervention techniques is a complex task considering the multiple parameters that come into play. In order to facilitate an overview on the process governing the accomplishment of such task, a simplified decision-making procedure is here proposed. The purpose is to offer a range of common scenarios related to cultural heritage failure and suggest how to proceed towards a solution. It should be underlined that the procedure outlined in this document should be considered as a general reference with an indicative value only. It is therefore advisable in all cases that a knowledge-based analysis, as described in D10.4, should be performed before progressing to any intervention.

4.1 DECISION-MAKING PROCEDURE

The proposed procedure involves interrelated operations. These can be summarized as follows: a) establishment of observed or expected failure mechanism; b) adoption of an adequate intervention strategy intended to prevent or enhance the response of the structure with respect to the established failure mechanism; c) individuation of specific actions that could be performed, within the objectives of the envisaged intervention strategy. This procedure, by narrowing down the possible intervention actions to be performed on a building, results in simpler selection of a feasible technique. The tables presented below aim at guiding users by providing the existing relationships between the different steps of the procedure.

a) establishment of observed or expected failure mechanism

The first step consists in determining the failure mechanism(s) observed or expected. The most common problems distinguishable in historical constructions can be organized into general categories (please refer to abacus in D3.1 for more details). These include:

- Insufficient capacity due to masonry characteristics or damage (table 1). The construction type, quality and state of preservation of masonry play a fundamental role in determining the capacity of a construction to sustain seismic actions. More specifically, the non-monolithic in-thickness behaviour of masonry becomes a governing parameter. Failure mechanisms include, for example, the separation between consecutive leaves which may be caused by decay of material in-time, combined with actions (vertical or horizontal) like the eccentric application of normal loads.

- Insufficient capacity due to elements characteristics (table 2). Building elements, as for example walls, pillars, floors and foundation, experience different failure mechanisms depending on their geometrical and material characteristics, location within the building and structural functionality. These mechanisms include rotations (overturning), displacements, deformations and cracking.

- Insufficient capacity due to overall arrangement (table 3). The interaction between building portions may produce failures such as in- plane sliding, hammering and out-of-plane damage. Irregularities in the characteristics of the building might result in a differential in the performance characteristics of parts of the structure and therefore produce context-specific failure mechanisms. Non-constrained trusts of building portions and structural elements such as vaults or roof structures may result in increased actions under seismic shaking for the structure.

- Insufficient capacity due to previous structural alterations (table 4). Structural modifications, such as roof or floor substitution with new RC or steel elements, can cause failure mechanisms such as overturning, crushing and local damage.

- *adoption of an adequate intervention strategy intended to prevent or enhance the response with respect to the failure mechanism*
- Once the failure mechanism is individuated, a corresponding intervention strategy must be selected. Table 1, 2, 3 and 4 relate the intervention strategies with the typology of failure mechanism. These strategies include:
- Improving the quality and mechanical performance of masonry by applying specific strengthening interventions (e.g., improving the quality of rubble masonry by grout injections and/or transverse tying, so as to fill the voids, give consistency to the masonry, and improve the connection between leaves thus avoiding their separation.
- Improving the capacity of macroelements by preventing occurrence of the weakest mechanisms. For example connections can be enhanced in order to avoid a simple façade overturning and to involve the lateral walls in the mechanism. Ties can be utilized to prevent a simple façade overturning and force an alternative three-hinged collapse mechanism.
- Fostering a box resisting scheme. For that purpose, the connections between elements and the in-plane stiffness of horizontal components may be improved.
- Increasing the dissipative capacity of existing structural members by implementing specific dissipative devices. The efficiency of the existing structure in dissipating energy can be improved by repairing damage, executing lime mortar injections for improving compactness and interlocking, and the improvement of connections by means of ductile solutions.
- Undertaking maintenance works only so to preserve, or even enhance, the seismic response of buildings originally built following, in a consistent way, construction tradition in a seismic place.
- Undertaking major works to remove inadequate structural members or counteract unconstrained trusts. The aim consists in recovering the original configuration of historical building with seismic resistant qualities. For instance, RC roofs and timber slabs may be substituted by new timber floors and roofs, and preexisting ties may be installed again.

Table 1 - Intervention strategies for failure mechanisms due to masonry characteristics.

<table>
<tr><th colspan="3">FAILURE MECHANISM</th><th>INTERVENTION STRATEGY</th></tr>
<tr><td rowspan="9">INSUFFICIENT CAPACITY DUE TO THE MASONRY CHARACTERISTICS OR DAMAGE</td><td rowspan="4">IN-PLANE MECHANISMS</td><td>Damages due to horizontal actions</td><td rowspan="9">-Improve masonry quality by strengthening

-Improve the capacity of macroelements

-Undertake maintenance works to preserve (and even enhance) the seismic resistant qualities

- Increase of the dissipative capacity of existing structural members</td></tr>
<tr><td>Homogeneous / good masonry quality</td></tr>
<tr><td>Mediocre masonry quality</td></tr>
<tr><td>Weak / poor masonry quality</td></tr>
<tr><td rowspan="5">OUT-OF-PLANE MECHANISMS</td><td>poor or absence of connection between the leaves</td></tr>
<tr><td>Partial connection of the leaves</td></tr>
<tr><td>Good connection between the leaves</td></tr>
<tr><td>Cladding separation</td></tr>
<tr><td>Overturning</td></tr>
</table>

Table 2 - Intervention strategies for failure mechanisms due to element characteristics.

FAILURE MECHANISM			INTERVENTION STRATEGY
INSUFFICIENT CAPACITY DUE TO THE ELEMENTS CHARACTERISTICS	IN-PLANE FOR WALL SECTS SEPARATED BY WINDOWS	Sliding	-Improve masonry quality by strengthening -Improve the capacity of macroelements (including their foundation when necessary) - Increase of the dissipative capacity of existing structural members -Improve the box behaviour
		Shear cracks	
	OUT-OF-PLANE MECHANISMS - VERTICAL STRIPS	Global overturning	
		Partial overturning	
		Corner overturning	
		Local out-of-plane collapse of a wall subjected to retaining actions	
		Arch effect in the thickness of the wall	
		Out-of-plane bending of load bearing walls	
	OUT-OF-PLANE MECHANISMS - HORIZONTAL STRIPS	Fixed-beam mechanism	
		Arch effect in the thickness of the wall: ultimate condition for masonry crushing	
		Arch effect in the thickness of the wall: abutments overturning	
	PORCH, LODGE, ARCADE OR COLONNADE	Soft storey	
		Local damages to pillars or columns due to bending action	
		Local damages to stone blocks columns or pillars due to bending action	
		Damages of pillars or columns due to long term compressive actions	
	FLOORS AND VAULTS	Head beams hammering	
		Vault or floor local collapses	
		Vaults damage due to spring rotation	
		Vaults damage due to in plane deformation	
	STAIRS		
	ROOF	Truss damage / movement / rotation	
		Roof covering damage	
		Overturning of tympanum spandrels	
	FOUNDATIONS	Lateral settlement	
		Central settlement	

Table 3 - Intervention strategies for failure mechanisms due to overall arrangement.

FAILURE MECHANISM			INTERVENTION STRATEGY
INSUFFICIENT CAPACITY DUE TO THE OVERALL ARRANGEMENT (INTERACTIONS BETWEEN BUILDING PORTIONS OR DUE TO IRREGULARITIES)	INTERACTIONS BETWEEN BUILDING PORTIONS	In plane shifting	-Improve the capacity of macroelements - Increase of the dissipative capacity of existing structural members -Improve the box behavior - Undertake major works to counteract unconstrained trusts
		Changes of stiffness due to irregularities in plan and height, often due to new additions	
		Out of plane and in plane damages of new additions	
		Non-constrained trusts of building portions and structural elements	
		Hammering between adjacent cells	
	MASONRY DISCONTINUTY	Cell hammering through connection element	
		Partial rotation	
		Discontinuity of plan configuration	
	OROGRAPHIC CONDITIONS	Different floors levels and building technology	
		Overturning mechanism in building in slope	

Table 4 - Intervention strategies for failure mechanisms due to previous structural alterations.

FAILURE MECHANISM			INTERVENTION STRATEGY
INSUFFICIENT CAPACITY DUE TO PREVIOUS STRUCTURAL ALTERATIONS	TRADITIONAL REPAIR TECHNIQUES	Local deformation at the floor level of the façade partially restrained	-Undertake major works to remove inadequate structural members -Undertake maintenance works to preserve (and even enhance) the seismic resistant qualities
	MODERN REPAIR TECHNIQUES	Out-of-plane mechanism in the presence of stiff and heavy roof structure	
		Local overturning of the wall due to tie beam hammering	
		V-shaped cracks near the façades corner – r.c. tie beam presence	
		Local damage due to the presence of r.c. tie beam	
		Partial overturning of the wall in presence of r.c. tie beam	
		In plane shifting caused by the presence of r.c. tie beam	
		Jacketing detachment due to the lack of connections	
		Low durability of jacketing due to insufficient thickness of the cover with consequent steel net corrosion	
		Local damage due to the lack of net overlapping	

b) *individuation of specific actions within those envisaged by the intervention strategy*

The adoption of a strategy with respect to a determinate failure allows a further step towards the definition of specific intervention actions. Table 5 relates the different intervention strategies with the specific intervention actions that could be carried out. The actions considered include:

- Improvement of strength or stiffness of vertical elements. This can be obtained by local reconstructions, lime mortar injection, crack repair and strengthening with composites or steel elements.
- Replacement of defective elements or weak materials.
- Repair of damaged members.
- Reconstruction of parts having experienced partial (or even total) collapses. This action normally requires strengthening in order to prevent from similar collapses in the case of future earthquakes.
- Improvement of strength or stiffness of horizontal elements. This may be obtained by including new stiff layers which can work as horizontal diaphragms or by fully substituting the existing systems.
- Improvement of connection between walls. More specifically, increment of the seismic capacity by producing a more efficient connection among walls, through the intensification of interlocking between blocks and/or the insertion of steel ties or anchors.
- Improvement of connection between floor slabs (or roofs) and walls. It can be achieved by means of ties or adequate anchors.
- Undertake measures to counteract unconstrained trusts of vaults or roof elements.
- Removal and substitution of inadequate structural members substituted in the past. Removal of RC floor slabs and roofs and substitution with compatible elements.
- Improvement of the connection to adjoining buildings. This is the case of urban complexes, groups of buildings or buildings surrounded by other buildings.
- Maintenance or improvement of the original dissipation capacity of original masonry structure. This may be attained by repairing existing cracks by means of deep injection or grouting with possible local reconstruction of the masonry or local substitution of deteriorated stones. In some cases, this operation should also involve the removal of superficial crack repairs, undertaken in the past, with execution of grouting or injection to ascertain a better recovery of the material continuity of masonry.
- Enhancement of energy dissipation capacity by means of specific dissipative devices such as anchors or anchor plates.

Table 5 - Specific intervention actions to be performed according to selected strategy.

INTERVENTION STRATEGY	SPECIFIC ACTION
Improve the quality of masonry and the capacity of macroelements	Improvement of strength or stiffness of vertical elements
	Replacement of defective elements or weak materials
	Repair of damaged members
Improve the capacity of macroelements and the box behaviour	Improvement of strength or stiffness of horizontal elements
	Improvement of connection between walls
	Improvement of connection between floor slabs (or roofs) and walls
	Removal and substitution of inadequate structural members
	improvement of the connection to adjoining buildings
Increase of the dissipative capacity of existing structural members	Repair of damaged members
	Enhancement of energy dissipation capacity by means of specific dissipative devices
Undertake only maintenance works to preserve (and even enhance) the seismic resistant qualities	Repair of damaged members
	Maintenance or improvement of the original dissipation capacity
	reconstruction of parts having experienced partial (or even total) collapses
Undertake major works to remove inadequate structural members	Repair of damaged members
	Removal and substitution of inadequate structural members
	Undertake measures to counteract unconstrained trusts

4.2 PROPOSED SOLUTIONS

The decision-making procedure described in the previous section aims at suggesting a series of specific actions to be performed in the context of failure scenario. In table 6, appropriate intervention techniques with respect to the specific action are suggested. Further details concerning the execution, application and the overall performance of the various intervention techniques can be found at the reference provided in the table.

Table 6 - Intervention techniques corresponding to specific intervention actions.

SPECIFIC ACTION	INTERVENTION TECHNIQUE
Improvement of strength or stiffness of vertical elements	Grout injection (Ref. D10.1, sec. 2.1.1.1 and sec. 2.1.1.2)
	Reinforcement with steel wires (Ref. D10.1, sec.2.1.2.1)
	Reinforcement using geo-nets (Ref. D10.1, sec. 2.1.2.2)
	Reinforcement with Belts (Ref. D10.1, sec. 2.1.2.3)
Improvement of strength or stiffness of horizontal elements	Composite strengthening of vaults extrados (Ref. D10.1, sec. 2.2.1.1)
	Composite strengthening of vaults intrados (Ref. D10.1, sec. 2.2.1.2)
	Strengthening with rammed earth (Ref. D10.1, sec. 2.2.2.1)
	Strengthening by substitution of single planking for tongue and groove planking (Ref. D10.1, sec. 2.2.2.2)
	Strengthening by substitution of single planking (90°) for double planking (45°) (Ref. D10.1, sec. 2.2.2.3)
Improvement of connection between walls	Strengthening of traditional timber connections using bolts (Ref. D10.1, sec. 2.1.3.1)
	Steel plates (Ref. D10.1, sec. 2.1.3.2)
	Steel flat bars inserted with NSM technique (Ref. D10.1, sec. 2.1.3.3)
	Grouted metallic anchor (Ref. D10.2, sec. 4.1)
	Anchor pins (Ref. D10.2, sec. 4.2)
	Grouted metallic anchors (Ref. D10.2, sec. 4.3)
Improvement of connection between floor slabs (or roofs) and walls	Metallic tie + steel angle (Ref. D10.2, sec. 4.4)
	Strengthening by various techniques (Ref. D10.2, sec. 4.5)
Enhancement of energy dissipation capacity by means of specific dissipative devices	Hysteretic/ frictional anchoring devices w/o monitoring and early warning system (Ref. D10.3, sec. 3.1)
	Stick-and-slip carpentry connection (Ref. D10.3, sec.3.2)
	Ductile anchors (Ref. D10.3, sec. 3.3)
Repair of damaged members	Grout injection (Ref. D10.1, sec. 2.1.1.1 and sec. 2.1.1.2) Local reconstruction
Removal and substitution of inadequate structural members	Strengthening by substitution of single planking for tongue and groove planking (Ref. D10.1, sec. 2.2.2.2)
	Strengthening by substitution of single planking (90°) for double planking (45°) (Ref. D10.1, sec. 2.2.2.3)
Reconstruction of parts having experienced partial (or even total) collapses	Local reconstruction
Maintenance or improvement of the original dissipation capacity	Grout injection (Ref. D10.1, sec. 2.1.1.1 and sec. 2.1.1.2) Local reconstruction (of cracked regions)

5 CONCLUSIONS

The multidisciplinary nature of interventions postulates the difficulty that professionals face in achieving the necessary knowledge to support the making of decisions. The main objective of these guidelines is indeed to outline the procedure required to support and control an adequate decision making process, aimed at the selection of a correct intervention to be performed.

Improving the seismic performance of historic buildings should be integrated into a comprehensive strategy based on periodic inspections by specially trained architects and engineers. This should consider regular inspection of architectural heritage and the development of regular maintenance programs.

It is useful for the sake of clarity to distinguish between a series of phases, intimately interrelated, that compose the integrated methodology: investigation phase, intervention phase, evaluation phase and management phase. Any general action on a historical structure should consider all of them according to unified approaches and criteria. Ideally, similar experimental and numerical tools should be utilized in all the phases, and an adequate and balanced technical and budgetary effort should be devoted to all of them.

It is advisable to refer to D10.4 for details concerning the recommended investigation strategies to be carried out on site. Furthermore laboratory assessment of structural connections is described in D10.2, including a set of procedures that can be used for the characterisation of structural connections, detailing set-up, samples, instrumentation and loading procedure.

In order to simplify the decision-making process a three-step procedure is defined including namely a) establishment of observed or expected failure mechanism; b) adoption of an adequate intervention strategy intended to prevent or enhance the response of the structure with respect to the failure mechanisms; c) individuation of specific actions that could be performed, within the objectives of the envisaged intervention strategy. Once specific actions are set, appropriate intervention techniques can be easily selected.

Recommended intervention techniques can be found in D10.1 (for details concerning design and execution of interventions on vertical and horizontal elements), D10.2 (for the description of a set of experimental procedures for the assessment of structural connections strengthened by various techniques) and D10.3 (for a summary of the various aspects related to the use of innovative devices for the strengthening of structural connections). The NIKER Catalogue (D3.6), available online at www.niker.eu, and aimed at knowledge-based optimization of interventions, defines the main design parameters and requirements for materials and intervention techniques

Details concerning the recommended evaluation strategies and the recommended management strategies to be performed during the maintenance period are presented in D10.4.