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Knowledge-based data warehouse of interventions for the protection of masonry historical heritage

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ABSTRACT: The great social, cultural and economic losses caused by seismic events on the cultural heritage assets have stimulated, in the last decades, a great research effort in the development of new integrated knowledge-based approaches and tools for their protection from earthquake-induced risk. Great amounts of data have been collected and several databases developed so far to gather information about peculiar aspects on the seismic behaviour of masonry historical buildings. The detail level of such databases is usually influenced by the required survey or intervention, with a generalised lack of information on the fundamental parameters that affect the seismic response, i.e. boundary conditions, used materials, types of connections and constraints, etc. A global systematization is required, to take advantage from the considerable and precious amount of available data, linking all information on the basis of the relation between construction typologies and elements and failure mechanisms, including also survey and monitoring procedures and tools available in literature. A new web-based data warehouse was developed within the FP7 European research project NIKER (2010–2012) "New Integrated Knowledge-based approaches to the protection of Cultural Heritage from Earthquake-induced Risk") to collect, systematize and analyse available data. This tool is able to link construction typologies and structural elements with collapse mechanisms into a matrix of interventions where end-users can easily select optimum solutions for the seismic improvement and assess the effectiveness, on the basis of pre- and post-intervention parameters. The interactive and dynamic functionalities, together with the capacity of cross-correlation of information at different knowledge levels and the sharing philosophy of a web-based system, make the data warehouse a powerful tool for a new innovative, integrated and knowledge based approach to the protection of cultural heritage, useful both to professionals and researchers.

1 INTRODUCTION

1.1 *State of the art*

Earthquakes represent the main risk factor for historical buildings in peacetime. This is particularly true in countries like Italy, Greece, Turkey, where history is rich of art and culture as well as great and frequent earthquakes. It is estimated that more than 41 million people in Europe (the 8%of the total) lives in high-risk areas and the economic loss due to earthquake damages in the same continent reached 35 billion euros in the last 30 years, quite apart from the loss of human lives (EM-DAT). In Bam, south Iran, a huge earthquake killed 25000 people and destroyed the greatest historical complex of adobe buildings 2000 years old (Wiles et al., 2007). The 1997 earthquake in Italy (Umbria and Marche regions) damaged over 8000 historical buildings, including the Basilica of S. Francesco and the frescoes by Giotto (Binda et al., 2004). A few years later, the 2009 earthquake in L'Aquila caused economic losses over 3 billion euros, living only the 23% of the buildings fit for habitation (D'Ayala, 2010). Slovenia and Morocco 2004, India 2005, China 2008, Italy 2012, the succession of events left behind death and inestimable losses of cultural heritage.

The only strategy to limit such losses is a preemptive identification of the seismic vulnerabilities with subsequent and adequate prevention plans as well as interventions respectful of materials and structural behaviour in case of already damaged structures.

The knowledge of the state of the art of historical buildings, of their location and state of repair assume a crucial and central importance in the preservation process of historical buildings. This led the Italian government in 2007 to issue a document stating the main guidelines for the evaluation and reduction of the seismic risk of the cultural heritage (Ministero per i Beni e le Attività Culturali, Circolare n. 26/2010) and other Italian public entities to start survey programs and data collection plans (ReLUIS, 2005).

New databases were implemented to collect all those data with the main limitations of their focusing on one single facet at a time: materials, construction types, failure mechanisms, intervention effectiveness, with a detail limited by the investigation purpose of every single project. A very substantial data collection containing history, geometric data, scheme of the structural system, detailed description of damages and failure mechanisms and subsequent interventions was compiled by a joined research group from the Universities of Padua and Milan (Binda et al., 2004).

1.2 *A new concept of data management*

The very potential of all that information can be delivered only correlating every aspect and gathering all data coming from the available sources, including knowledge about on-site evaluation methods and surveying procedures already available in literature (Maierhofer et al., 2006) and material properties and intervention techniques coming from lab experiments.

A tree-year international programme NIKER (New Integrated Knowledge-based approaches to the protection of cultural heritage from Earthquake-induced Risk) was carried out in 2010–2012 by a group of 18 partners led by University of Padua to close the loopholes both on the technical knowledge of the behaviour of historical buildings under seismic actions and on the availability of a practical and adequate tool to properly manage all the information.

A conceptually new software tool was developed with the ability not only to collect and analyse data, but also to suggest solutions as well as to help finding new qualitative and quantitative correlations among all involved factors. This software, defined for its features a ‘data warehouse’, was tested and validated by the on-site and in-lab experimental programme carried on by all 18 partners and represents the state of the art on the preservation of historical buildings.

2 HISTORICAL BUILDINGS

2.1 *Types, elements and materials*

The first step was the identification of constructive types, elements and materials, and their classification into categories suitable to structure and aims of the software tool. All elements were categorised by their use and static behaviour under seismic actions.

Four construction types have been identified: buildings and palaces, religious buildings, towers and free-standing elements.

Buildings and palaces present a box-like structure with vertical bearing elements and horizontal load-distributing ones. Religious buildings are mainly characterised by the absence of in-between horizontal diaphragms and by the presence of peculiar elements such as transepts, domes, apses, façade, triumphal arch. They react to seismic actions with distinctive failure mechanisms, mostly obtained by a mere combination of the autonomous failure mechanisms of the single components (Ministero per i Beni e le Attività Culturali, Circolare n. 26/2010). The group of towers includes bell towers, minarets and all structures with a high height-width ratio. Isolated columns, parts of side walls and other partial ruins gathers into the group of free-standing elements.

The categorisation of construction elements was done only considering the static-operational behaviour, grouping all vertical elements, bearing and not bearing, all horizontal components, with both connection and support purposes, arches, vaults and domes, and all types of connections. Six categories were identified: *Walls*, *Floors*, *Roofs*, *Arches* and *Vaults*, *Columns* and *Sub-assemblage connections*.

Material and its preservation status determine the resistance capacity of masonry under seismic action. The global mechanical behaviour is much more important than the resistance of the block themselves (Borri et al., 2009). This makes geometry, weaving, physical, mechanical and chemical characteristics of stone, mortar and bricks as well as of the whole composite material extremely important (Binda et al., 2000).

Table 1 shows materials and material types identified for each construction element. The differentiation was done in relation to their geometric manufacturing, static behaviour and response to seismic actions.

2.2 *Parameters and performance indicators*

The second step was the definition of parameters and performance indicators pre and post-intervention. Parameters are measurable physical or mechanical quantities, which were assigned to four different groups of objects: *existing structural element*, *components*, *post-intervention structural element*, *reinforcement*.

The first group of parameters identified the characteristics of the entire element, such as a wall or a floor, before an intervention. The second referred to the single components such as stone, brick, mortar or wood. The third group characterised the structural element after the intervention. The fourth group was related to all reinforcement

Table 1. Materials and material types identified for each construction element defined in the data warehouse.

Wall	Stone masonry	Single-leaf Multi-leaf
	Brick masonry	Single-leaf Multi-leaf
	Earthen masonry	Adobe
	Monolithic earth materials	Rammed earth Cob
	Timber reinforced masonry	Timber tied stone masonry Timber framed masonry
Floor	Timber	Simple unidirectional floor Bidirectional floor
	Steel	Steel beams and brick vaults
Roof	Timber	Non thrusting structure—truss (rafter without flexure) Non thrusting structure—truss (rafter under flexure) Thrusting structure
	Steel	Truss structure
Arch / Vault	Brick—Stone	Arch and barrel vault Groin vault Cloister vault Ribbed vault and dome
	Adobe	Barrel Vault Domes
Columns	Brick—Stone	Monolithic columns Drum columns Masonry Pillars
Sub-Assemblage Connections	Connection horizontal to vertical structure	Connection between (stone/brick) masonry walls and floor/roof structures Connection between stonework wall and timber floor Timber laced connections in rubble infill stonework building Connection between earthen walls and floor/roof structures
	Connection vertical to vertical structure	Connection between orthogonal (brick/stone) masonry walls Connection between orthogonal stonework walls Corner connection between orthogonal brickwork walls Connection between stonework wall and vertical timber frame Timber laced connections in rubble infill stonework building Connection between orthogonal earthen walls
	Roof carpentery connections	Halved dove tail connections

and additional elements, such as steel or FRP bars or concrete slabs.

This kind of differentiation permitted an accurate comparison between the pre and post-intervention conditions of the element and a specific evaluation of the influence of additional materials.

The performance indicators were the properties involved by a failure mechanism. Each failure mechanism mobilises some of the parameters describing the element. The components of the shear response, for instance, are fundamental if evaluating an in-plane failure mechanism of a wall, but are not involved during an out-of-plane mechanism. The tensional stress causing the first crack in pillars has a crucial role in the creep events, but not in other kinds of failures (Saisi et al., 2004). Some performance indicators such as boundary confinement or section monolothism were not measurable, but contributed to properly describe the mechanical response.

2.3 *Failure mechanisms*

Functional categories were identified also for failure mechanisms, identifying homogeneous groups with similar dynamic response to seismic actions. Such categories were defined for each construction element.

All in-plane failure mechanisms, for instance, were gathered in one single group and the same was done for out-of-plane overturning, out-of-plane flexure and layer separation.

The relation between failure mechanisms and interventions was also considered while grouping the mechanisms. This helps professionals to better identify the best interventions connected to a set of failure mechanisms, as well as researchers to better compare parameters in case of similar mechanical response. The dynamic structure of the software application allows in every moment the modification of every categorisation, as well as the re-definition of all categories, to better reflect to the level of investigation known and required. This high-level feature provides a continuous adaptation to all new information which can be collected in future.

Table 2 shows the failure mechanisms already defined in the data warehouse, grouped by construction element.

2.4 *Interventions*

Nowadays, the interventions on historical heritage aim to strengthen, repair and stabilise the structure, mostly after damages by seismic actions. Such actions must respond to recognised principles of preservation balanced with static requirements. Specific criteria, identified for a proper intervention, are: minimum intervention, durability, reversibility (removability, substitutability), compatibility, preservation of authenticity, descriptive fulfilment, reliability and monitoring and control (Carbonara, 1997; Manieri Elia, 2010).

Interventions on walls aims at re-establish stability against out-of-plane separations (improving connection within the thickness in case of multilayer walls), or in-plane repairing or strengthening. Grout injections (Figure 1), transverse ties, reinforced repointing may be considered to improve the out-of-plane response of the wall, whereas simple repointing, metallic strips and diagonals, crack stitching and jacketing with reinforced sustainable plasters (as TRM, Textile Reinforced Mortar) and the use of fibrous composite materials are increasingly applied for the in-plane strengthening.

Table 2. Failure mechanisms already defined in data warehouse, grouped by construction element.

Construcion element	Failure mechanism
Wall	In-Plane Failure Out-of-Plane Overturning Out-of-Plane Flexure Layer Separation
Floor	Inadequate out-of-plane bending strength and stiffness Inadequate in-plane stiffness Slipping at supports Beam-vault separation Rusting of steel beam (at support, web and/or flange) Degradation and breakage of brick material Mortar disintegration
Roof	Inadequate bending strength and stiffness Inadequate in-plane stiffness Slipping at supports Material degradation Out-of-plane instability Joints failure
Arch/Vault	Displacement of the supports Differential settlement of the piers Longitudinal sliding Load variation
Columns	Compression Compression & Creep Buckling Crumbling and loss of symmetry Cracks and loss of monolithicity Incompatible material supplements Inadequate support
Sub-Assemblage Connections	Separation of structural elements

Figure 1. Grout injection procedure. (a) General overview of the process. (b) Drilling holes in mortar joints. (c) Fixing plastic pipes. (d) Injecting grout. (NIKER, WP3, Deliverable 3.2).

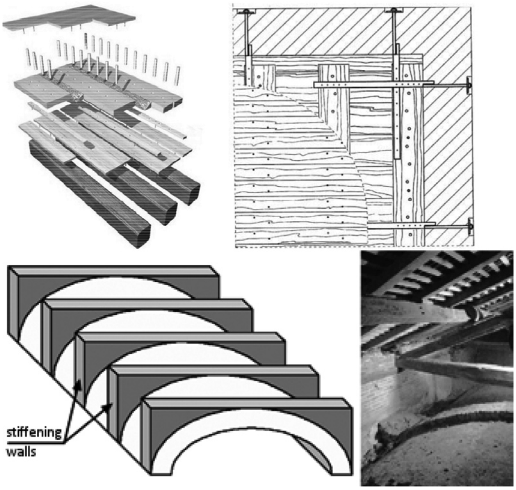

Figure 2. Strengthening interventions for the optimization of horizontal elements performance: (a) Wood-wood technique and detail of the connection to the walls for wooden floors; (b) stiffening elements in barrel vaults. (NIKER, WP3, Deliverable 3.2).

Material degradation may be also restored by structural repointing for the mortar joints and local rebuilding or unit substitutions for the resisting elements.

Floors and roofs often requires improvement in terms of in-plane stiffness, to counteract horizontal actions, and of connections with the adjacent vertical bearing structures. Diagonal strips, overlapping of planking or other dry connection techniques, as well as composites, possibly applied with compatible materials, may be used.

Arches and vaults, as well as pillars and columns, are efficiently repaired and strengthened with composites systems, particularly applied with compatible matrices (SRG, Steel Reinforced Grouts, TRM, etc.) (Figure 2).

Connections may refer to traditional tying, but also to smart systems.

The available documentation on interventions is extremely varied. A form has been edited to evenly organize all available information into the data warehouse. A total of 97 interventions were collected, some of which very peculiar, thanks to the contribute of private partners of the NIKER project.

3 THE DATA WAREHOUSE NIKER

3.1 *Procedural approach*

The implementation of a software application to properly manage all this information was performed. It was meant to be a structured container of all required data and a fast and efficient search tool, capable of extract the required information at any level of complexity and, at the same time, suitable to correlate the values of the parameters both before and after an intervention for a given category and among the categories themselves. Moreover, the software was required to suggest at a glance which failure mechanisms are related to a given construction type and material, and the best interventions experienced in literature for such combinations.

Those peculiarities delineated the software as an important and efficient tool both for design and research, which can be referred to as “data warehouse”, after the definition by William H. Inmon in the ‘70 s for systems deputed to reporting and data analysis (Inmon, 1992).

This tool was used and validated by all partners of the NIKER project to gather and systematise data from different historical contexts (Cantini et al., 2012; Giacometti, 2014).

The parametrisation of the information and its organisation within the procedures of the data warehouse was a relevant result, since the actual usability of the information is the main issue of most of the existing data management systems. The innovative graphical-conceptual layout can satisfy both designers, looking for a decision-support tool, and researchers, aiming to simplify the recognition of mechanisms and to define new models of structural behaviour.

The logical sequence of operations should follow the natural process of analysis of an intervention plan on a structure either already damaged by an earthquake or subjected to a pre-emptive reinforcement action. In both cases, the starting point is the definition of all the measurable physical and mechanical parameters, which define the construction element and its constitutive materials.

The second step was the definition of the failure mechanism involved with the identification of its performance indicators, both measurable and descriptive. The measurable ones were used to filter the parameters of the element while the descriptive ones contributed to the choice of the proper intervention.

The third step was the choice of one or more interventions suitable to the given combination of element and failure mechanism. Each intervention can modify the measurable parameters of either the element or the material and, in some cases, also the failure mechanism itself can be modified. Moreover, new materials can be inserted and thus new measurable parameters. This process can be replicated for all the elements of a structure.

The publications assume an essential role within the complex structure of the data warehouse. They assure the reliability of the involved parameters and their values, since values not related to any scientific publication are not accepted, and allow the correlation among the values.

Figure 3 shows the flow scheme of the data warehouse for data input and analysis, and Figure 4 shows the procedural approach for the choice of the proper intervention.

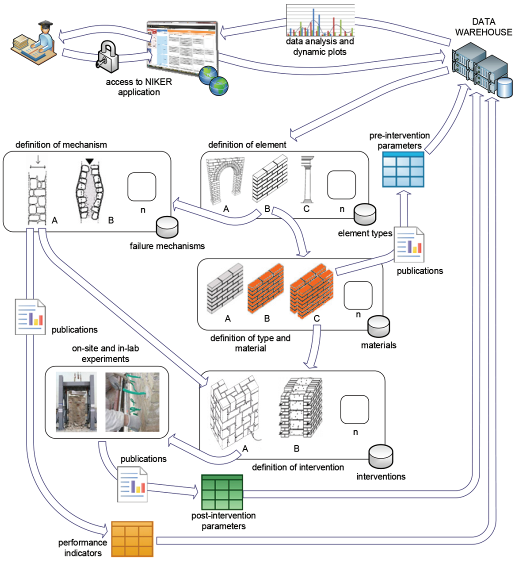

Figure 3. Flow scheme of data warehouse for data input and analysis.
*Sketches of interventions are after (Caleca et al., 1999; Valluzzi et al., 2005); pictures of experimental tests are after (Modena et al., 2013; Modena et al., 2009); sketches of the failure mechanisms are after (Doglioni et al., 2007; Giuffrè 1993).

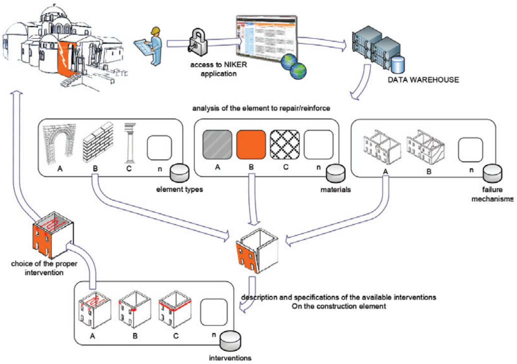

Figure 4. Procedural approach for choice of the proper intervention.
*Sketch of church symbolises byzantine church of St. Nicholas in Myra/Demre, Turkey [http://www.stnicholascenter.org/pages/myra-church (last visit 19/01/2014)]; sketches of failure mechanisms are after (Giuffrè, 1993; Carrocci, 2001).

3.2 *Logical concept and graphic layout*

The entity-relationship diagram reported in Figure 5 defines two sets of objects and relations, which represent the key points of the whole structure. The first set gathers element specifications and failure mechanisms with interventions. The second set gathers the values of all parameters with publications.

The first set gains its greatest descriptive efficiency if considering, for each construction element, a tree-dimension space, which axes represent respectively the element specifications, the failure mechanisms and the interventions. The main plane represents a table with finite dimension cells, which correlates element specifications to failure mechanisms. Each cell reflects a real situation where one or more interventions can be applied. The interventions lay on the vertical axis, as shown in Figure 6a. The second set has no graphical representation.

The modern web computer graphics still do not permit an easy representation of a three-dimension layout. A two-dimension adaptation was then developed, transforming the axis of the intervention, hierarchically subordinate, into a list.

The adapted layout was a table with rows representing the element specifications and columns representing the failure mechanisms. Each cell identified by the crossing of a specification with a mechanism contains the list of all the interventions compatible with that combination, as shown in Figure 6b.

All components in both the three-dimension and the two-dimension layouts were identified by a different colour, to improve the usability of the software.

Figure 5. Entity-relationship diagram of data warehouse.

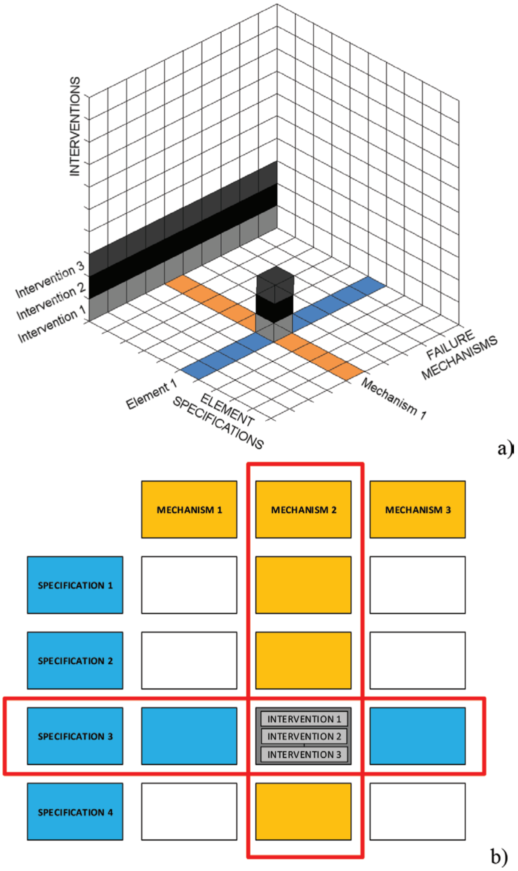

Figure 6. a) Logical representation of relationship among element specifications, failure mechanisms and interventions; b) Graphical layout of relationship among element specifications, failure mechanisms and interventions.

Figure 7. Graphic layout of data warehouse.

Figure 7 shows the final graphic layout, where colours are conferred a specific consideration, with a chromatic coherence preserved both in the software and in the documentation.

3.3 *Data analysis*

One of the main benefits of the data warehouse is a nearly instant evaluation of the scarcity of information and the subsequent need of further investigations and new applications. Different icons were associated to material sub-types, as well as to each intervention associated to the pair material sub-type and failure mechanism, to visually help the identification of such inconsistencies. More specifically, the icons show the lack of parameters or the lack of values before as well as after the intervention.

The level of knowledge is summarised in Table 4 for both materials and material sub-types. Table 3 defines the levels Table 4 refers to. The post-intervention evaluation was based only on the existence of known values of the parameters characterising the material after the intervention. The pre-intervention analysis tries to take into account also the lack of parameters. This attempt had the only purpose to highlight the need of in-depth analyses, since the shortage of parameters was mainly due to the difficulty of find data in the scientific literature. A negative assessment should represent an incentive to increase both the number of users

Table 3. Definition of level of knowledge of parameters in the data warehouse.

Pre-intervention level of knowledge (presence of values and lack of parameters)	
Excellent	Parameters are defined and all or almost all of them have values (90–100%)
Very good	Parameters are defined and most of them have values (80–90%)
Good	Parameters are defined and many of them have values (60–80%)
Sufficient	Parameters are defined and more than half of them have values (50–60%)
Insufficient	Parameters are defined and less than half of them have values (30–50%)
Inadequate	Parameters are defined and few of them have values (0–30%)
None	No parameters are defined (0%)
Post-intervention level of knowledge (presence of values)	
Excellent	All interventions or almost all of them have values (90–100%)
Very good	Most interventions have values (80–90%)
Good	Many interventions have values (60–80%)
Sufficient	More than half of the interventions have values (50–60%)
Insufficient	Less than half of the interventions have values (30–50%)
Inadequate	Few interventions have values (0–30%)
None	No intervention has values (0%)

Table 4. Level of knowledge of the parameters as reported by the data warehouse for both materials and material sub-types.

Material	Material sub-type	Pre-intervention level of knowledge	Post-intervention level of knowledge
Stone masonry	Single-Leaf	Very good/Excellent	Insufficient/Sufficient
	Multi-Leaf	Excellent	Insufficient/Sufficient
Brick masonry	Single-Leaf	Very good	Insufficient/Sufficient
	Multi-Leaf	Very good/Excellent	Insufficient/Sufficient
Earthen masonry	Adobe	Excellent	Sufficient
Monolithic earth materials	Rammed Earth	Very good	Inadequate/Insufficient
	Cob	Excellent	Inadequate/Insufficient
Timber reinforced masonry	Timber framed masonry	Excellent	Insufficient
	Timber tied stone masonry	Very good/Excellent	Inadequate/Insufficient
Timber floor	Simple unidirectional floor	Excellent	Very good
	Bidirectional floor	Inadequate	Inadequate/Insufficient
Steel floor	Steel beams and brick vaults	Inadequate	Inadequate/Insufficient
Timber roof	Non thrusting structure—truss (rafter under flexure)	Insufficient	Inadequate
	Non thrusting structure—truss (rafter without flexure)	None	None
	Thrusting structure	Inadequate	Inadequate
Steel roof	Truss structure	None	None
Brick—stone arch / vault	Arch and barrel vault	Excellent	Good
	Groin vault	Inadequate	Excellent
	Cloister vault	Inadequate	Excellent
	Cloister vault	None	None
Adobe arch / vault	Barrel Vault	None	None
	Domes	None	None
Brick—stone columns	Monolithic columns	Excellent	Inadequate
	Drum columns	None	None
	Masonry Pillars	Excellent	Insufficient
Connection horizontal to vertical structure	Connection between (stone/brick) masonry walls and floor/roof structures	None	Inadequate
	Connection between stonework wall and timber floor	Very good/Excellent	Inadequate
	Timber laced connections in rubble infill stonework building	None	Inadequate
	Connection between earthen walls and floor/ roof structures	None	Inadequate
Connection vertical to vertical structure	Connection between stonework wall and vertical timber frame	None	None
	Connection between orthogonal stonework walls	Insufficient	Excellent
	Corner connection between orthogonal brickwork walls	Excellent	Excellent
	Connection between stonework wall and vertical timber frame	None	None
	Timber laced connections in rubble infill stonework building	None	None
	Connection between parallel (brick/stone) masonry walls	None	None
Roof carpentery connections	Halved dove tail connections	Excellent	Inadequate/Insufficient

of the software and the investigation fields. If by one side the data warehouse pretends to be a tool for researchers, of course without research it cannot succeed.

4 CONCLUSIONS

The data warehouse presented here is a tool extremely interactive, which provides many features for professionals and researchers. The first one, representing a key point of the whole system, is the capability to correlate element types, failure mechanisms and intervention. This feature is achieved with a technical and graphic solution very innovative in the field of the protection of cultural heritage and permits an immediate identification of the most suitable interventions, in a defined context.

Another relevant result is the ability of the software application. To correlate parameters and performance indicators which characterise the element types, the failure mechanisms and the interventions.

This interactive correlation can be deepened to the level of the parameter values. An automatic generator of dynamic plots was developed to provide users with as much freedom as possible when choosing what to correlate and how. The proficiency of this very powerful tool can be continuously improved if provisioned with data coming from new experiments and researches.

The data warehouse was developed as a web application and is on-line at the address:

http://niker.dicea.unipd.it

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