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AHP-BASED METHODOLOGY INTEGRATING MODERN INFORMATION TECHNOLOGIES FOR HISTORICAL MASONRY CHURCHES DIAGNOSIS

1. Introduction

The recent seismic events have shown that masonry churches represent a building typology particularly at risk from earthquakes. In fact, in the last decade, seismic and structural vulnerability has been widely discussed by the scientific community. Latest post-seismic observations in Italy (e.g. Umbria and Marche, 1997; L'Aquila, 2009; Emilia, 2012; Central Italy, 2016) have made the issue of the protection of historical and cultural architectural heritage of fundamental importance. Moreover, the surveys carried out after the recent earthquakes have shown that the effectiveness of connections, the damage of wooden elements or the problems due to humidity are important issues. They should be added to the analysis of the well-known parameters related to structural damage and masonry quality to perform a complete investigation (Borri *et al.* 2017). Many criteria, phenomena and criticalities data are necessary in order to obtain an exhaustive structural diagnostic of a masonry building. The knowledge process starts from an in-depth investigation with the aim to consider different aspects of the construction: building history, geometry, used technology, materials' characteristics and degradation, cracks and deformations.

In the analysis process about masonry building degradation, the difficulty is linked to the heterogeneity of the factors that participate at the evaluation of the building residual performance. The Analytic Hierarchy Process (AHP), as multicriteria decision making tool, performs an exhaustive analysis thanks to the possibility of considering many criteria and giving them a calibrated weight. This method became popular in different areas of construction (Schöttle, Arroyo 2016). Starting from the project stage, Hsieh *et al.* (2004) used AHP, identifying key selection criteria in order to decide on the contractor selection, and Wong and Li (2008) in order to analyze the selection of the intelligent building systems. AHP has been used also for systematic evaluation of many factors such as building efficiency, safety, user comfort, reliability, functionality, and maintainability, for characterizing the design work, evaluating the soft benefits in comparison with costs (Reza *et al.* 2011; Kwon *et al.* 2014; Martiradonna *et al.* 2019). Li *et al.* (2013) used it to evaluate the work sites safety and the management, while Das *et al.* (2009) for the construction management.

Cultural heritage monitoring and preservation is a developing discipline which consists in the application of intelligent technologies within cultural sites. It is widely used to monitor different parameters such as the church thermo-hygrometric conditions, light and air quality in order to preserve the wall paintings and architectural monuments (Dorokhov, Pintelin 2018). There are many parameters to take into account to obtain a complete overview of the performance of masonry churches. Masonry quality, cracking patterns, connections or wood elements are just some of the parameters to be analyzed in order to obtain an exhaustive preliminary structural diagnostic.

In this paper, AHP (Saaty 2008) is used to study in deep the characteristics involved in the masonry structures performances and set up a novel visual survey-based methodology to perform diagnostics. A key point of the proposed method is the effective evaluation of suitable condition ratings, which depend on a very large number of possible damages, degradations or criticalities affecting historical masonry churches. More in depth, a set of indexes is defined and calibrated in order to perform an exhaustive analysis of masonry churches. It allows to consider the following characteristics: i) masonry quality and related state of conservation by evaluating the Masonry Index (I_M), ii) the effectiveness of connections between walls and floors by evaluating the Connection Index (I_C), and iii) wood floors quality and related state of conservation by evaluating the Wood Floors Index (I_W).

In this field, the AHP approach can be particularly effective with the purpose of considering qualitative and quantitative data and analyze the complex problem through a multi-criteria analysis. The resulting condition ratings can be easily implemented in an information system called Decision Support System (DSS) which supports maintenance and monitoring decision-making activities (Sangiorgio *et al.* 2017).

2. AHP-based methodology

The use of the AHP methodology to quantify the weights of the macro-element collapse modes is based on the well-known Saaty's 3-steps Method (Saaty 2008): 1) hierarchical structuring of the the problem; 2) weight evaluation; 3) summary of priority. Starting from a decision problem, the first

A	1	2	…	N
1	1.0	$a_{1,2}$	…	$a_{1,n}$
2	$1/a_{1,2}$	1.0	…	$a_{2,n}$
…	…	…	1.0	…
n	$1/a_{1,n}$	$1/a_{2,n}$	…	1.0

Tab. 1 – The generic matrix of judgments A.

step consists in structuring the problem according to a hierarchical scheme. To this aim, the goal of AHP is identified and the related criteria, sub-criteria and alternatives to reach the goal are determined.

The second step of weight evaluation is the core of the method and provides the weights that are necessary for generating the ranking. It is possible to individually analyze each aspect of the decision problem by considering n ordered criteria (i.e., criteria, sub-criteria or alternatives in relation with criteria or sub-criteria), compared each, using the Saaty's Fundamental scale (Saaty 2008). The result is a n×n judgments matrix A (Tab. 1). By solving an eigenvector problem, the AHP permits determining the weights. In addition, in order to verify the coherence of the assigned judgement and the reliability of the result, Saaty's method defines the Consistency Index (CI). In fact, on the basis of several empirical studies, Saaty concluded that the value of Consistency Ratio CR< 0.10 is acceptable (Saaty 2008). The third step, i.e. the summary of priority, is performed to determine the global ranking and the global weights: the weight of criteria, sub-criteria or alternatives are combined according to the hierarchical scheme defined in the first step of the AHP by following the theory of Saaty (2008).

3. AHP application

3.1 *Step 1: the problem of the masonry damage and quality*

The first step of AHP is applied to investigate the loss of churches masonry structural performances due to many phenomena and typologies of construction criticalities and damages. Many qualitative and quantitative aspects and criteria can be considered to obtain the hierarchical scheme of the masonry building performance (Fig. 1). In particular, three macro-criteria are studied: the Masonry performance, the effectiveness of Connections and the conservation state of Wood Floor. The first macro-criterion used to determine the structural performance concerns the quality of the Masonry. In turn, the five criteria showed in Fig. 1 are considered.

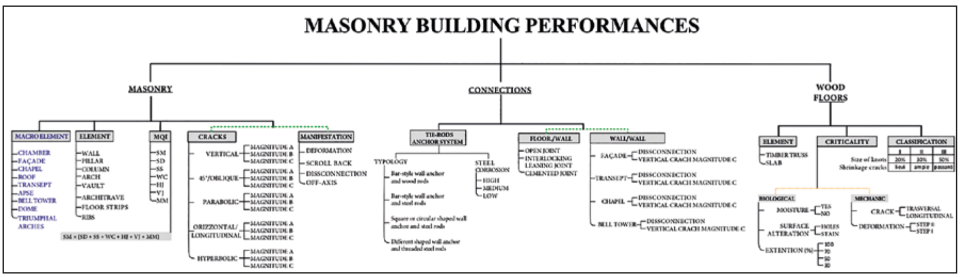


Fig. 1 – Structure of the problem: historical masonry churches diagnostics.

The first criterion classifies the macro elements of the churches (chamber, façade, chapel, etc.) (Fig. 1). The second one concerns the elements of the church that can be damaged (wall, pillar, column, etc.). The third criterion is fundamental because it exploits an existing methodology called Masonry Quality Index (MQI) method (Borri *et al.* 2015). The fourth criterion is related with the Masonry performance and concerns cracks or criticality manifestation (including deformation, scroll back, disconnection) affecting the construction. The classification of the damages is set according to the classification model of Sangiorgio *et al.* (2018). In this approach, they are decomposed and coded on the basis of Cracks (vertical, oblique, etc.) and each Cracks-type is further classified according to the severity level of the damage (Magnitude A, B or C where C is the most serious damage). Finally,

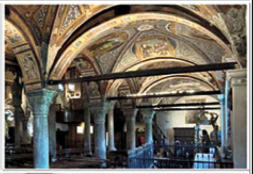
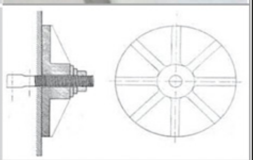
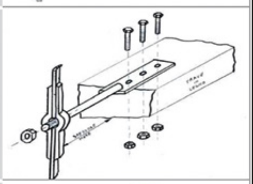
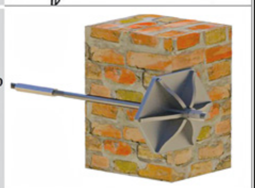
Tie Rods evolution over time		
Before 1500 A.D.	–Wood Tie rods; –Strong aesthetic impact; –High weight; –Problems related to the degradation both of wood and steel; –Bar style wall anchor.	
Between 1500 and 1700 A.D.	–Steel Tie rods; –Bar style wall anchor; –Clamping techniques not very effective.	
Between 1800 and 1900 A.D.	–Advanced clamping systems; –Static or aesthetic needs; –Stiffening ribs; –Multiple threaded and tensioned rods; –Bolted systems.	
	–Bilateral connection on the wooden beams; –Bolted systems.	
After 1900 A.D.	–Advanced clamping systems; –Static or aesthetic needs; –Corrosion protection by austenitic or duplex steels; –Polymeric sheath inside between steel and masonry to avoid direct contact; –Remaining voids filled by injection of resins; –Chain joining via sleeve for threaded junction, clamped, clamped, bolted or grooved; –Bars equipped with threaded ends for clamping;	

Fig. 2 – Study of the Tie Rods evolution over time.

also the criterion of the criticality manifestation is considered by identifying any masonry deformation, disconnection or scroll backs.

The second macro-criterion considers the efficiency of wall-to-floor and wall-to-wall connections, since they assure the correct structural behaviour of the masonry and prevent the occurrence of most mechanisms of local collapse. The third macro-criterion represents the state of conservation of wood floor that takes into consideration: 1) the typology of damaged elements (timber truss or slab), 2) the wood criticality, 3) the classification of wood quality to take into account the intrinsic vulnerability of the material.

3.2 *Step 2: weight evaluation*

The second step of AHP analyses each aspect of the hierarchical scheme of the masonry building performance (Fig. 1) in order to weight criteria and parameters involved. This section exploits previous studies regarding every aspect engaged in masonry structures in order to obtain the judgment matrices: seven are used to analyze criteria and parameters of the Masonry macro-criterion, five matrices are evaluated to obtain criteria and parameters weights of the Connections macro-criterion and eight matrices are estimated to provides weights related to the Wood Floors macro-criterion.

To provide an example, the weight calculations of the tie rod anchor system related to the macro criterion Connections are showed. The Tie-Rods effectiveness is related to the typology (classified by year of manufacture) and to the level of steel corrosion as discussed in the structuring of the problem (Fig. 2). A qualitative analysis is carried out by pairwise comparisons of the alternatives, based on the preliminary study. It permits to achieve the judgment matrix. The weights normalized between 0 and 1 were obtained by solving the eigenvector problem defined in the Saaty's theory. The resulting matrix (Tab. 2) satisfied the Consistency Ratio requirement CR<0.1 and this verification allows to validate the coherence of the obtained weights.

3.3 *Step 3: summary of priority and condition ratings*

After weighting, the condition ratings can be defined. This operation coincides with the third step of the summary of priority. The formulas of condition ratings are obtained by multiplying each criteria weight by the

Typology	a	b	c	d	CR	$w_{6,1}$
Before 1500 (a)	1.0	1.8	2.5	3.0	0.01	1.00
Between 1500-1800 (b)	0.6	1.0	2.0	2.8		0.69
Between 1800-1900 (c)	0.4	0.5	1.0	1.9		0.41
After 1900 (d)	0.3	0.4	0.5	1.0		0.26

Tab. 2 – Judgment Matrix for the typology parameter, weights, and CR.

Criterion	**CONNECTIONS**							
Sub-criterion	**TIE-RODS**				**FLOOR/WALL**	v_8	**WALL/WALL**	v_9
	TYPOLOGY	v_6	**STEEL CORROSION**	v_7				
Parameters	Bar-style... and wood rods	$w_{6,1}$	HIGH	$w_{7,1}$	OPEN JOINT	$w_{8,1}$	FAÇADE	$w_{9,1}$
	Bar-style... and steel rods	$w_{6,2}$	MEDIUM	$w_{7,2}$	INTERLOCKING LEANING JOINT	$w_{8,2}$	TRANSEPT	$w_{9,2}$
	Square... anchor and steel rods	$w_{6,3}$	LOW	$w_{7,3}$	CEMENTED JOINT	$w_{8,3}$	CHAPEL	$w_{9,3}$
	Different... and threaded steel rods	$w_{6,4}$					BELL TOWER	$w_{9,4}$
							DISSCONNECTION	$w_{9,j,1}$
							VERTICAL CRACK C	$w_{9,j,2}$

Fig. 3 – Connections, macro-criterion and weights.

sub-criteria weight and adding the results, as in the classical AHP procedure. To this aim three condition ratings are defined: Masonry Index (I_M), Connection Index (I_C), Wood Elements Index (I_W). To provide an example, the I_M can be calculated by exploiting the weights obtained in the AHP step 2. Fig. 3 shows the association to the criterion, sub-criterion or alternative with the relative weights achieved with the matrices of comparison. The proposed indexes are useful to quantify the performance and condition of every element of a church (wall, pillar, column, slab, etc). Let us assume that we need to analyze a component of a masonry church, belonging to a specific macro-element and with a particular combination of MQI, Cracks and Manifestation. The condition rating to quantify the performance of the masonry criterion is evaluated by the following equation in accordance to Sangiorgio *et al.* (2019):

$$\boldsymbol{I_M} = v_1 * w_{1,j} + v_2 * w_{2,j} + v_3 * [w_{3,1} * (\textstyle\sum_{j=2}^{7} w_{3,j} * w_{3,j,k})] + v_4 * w_{4,j} * w_{4,j,k} + v_5 * w_{5,j} \quad (1)$$

where v_i are the weights associated to the sub-criteria and $w_{i,j}$ are the weights associated to the parameters of the analysis. Analogously, it is possible to evaluate the performance of Connection. The Connection Index (I_C) is evaluated by the following formula:

$$\boldsymbol{I_c} = v_6 * w_{6,j} + v_7 * w_{7,j} + v_8 * w_{8,j} + v_9 * w_{9j,} * w_{9,j,k} \quad (2)$$

and the Wood Floors Index (I_W) is evaluated by the following formula:

$$\boldsymbol{I_w} = v_{10} * w_{10,j} + v_{11} * w_{11,j} + v_{12} * w_{12,j} + v_{13} * w_{13,j} + v_{14} * w_{14,j} + v_{15} * w_{15,j} \quad (3)$$

Finally, the global condition rating (global index structure named $I_{STRUCTURE}$) is evaluated as a weighted average of the I_M, I_C, and I_W including all the components of the structure and it is ranging between 0 and 10 (Sangiorgio *et al.* 2018).

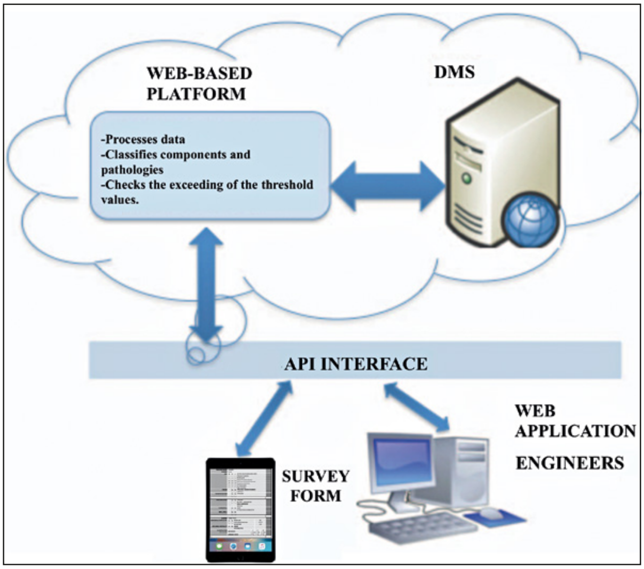


Fig. 4 – The DSS Architecture.

4. The integration of the AHP-based approach in DSS

The proposed approach can be exploited to set a spreadsheet useful to a rapid survey of an historical church. In particular, a suitable Survey form (Fig. 5) implementable in a DSS is developed for a fast survey and to evaluate the condition ratings by exploiting equations (1-2-3).

4.1 *DSS architecture*

The architecture of the proposed DSS is constituted by five components (Fig. 4):

1) A Data Management System (DMS) which collects the information provided by the users by the Survey form.
2) A web-based platform, that represents the intelligence of the system. This platform processes the Survey form data, classifies the churches components and calculate the condition ratings.
3) The Survey form consisting of a suitable spreadsheet implementable in an APP for smart devices.
4) Web application used by technicians to display the reported Survey form history, the register information about the church.
5) Application Programming Interface (API) connecting the Survey form (APP) and the web application with the web-based platform and the DMS.

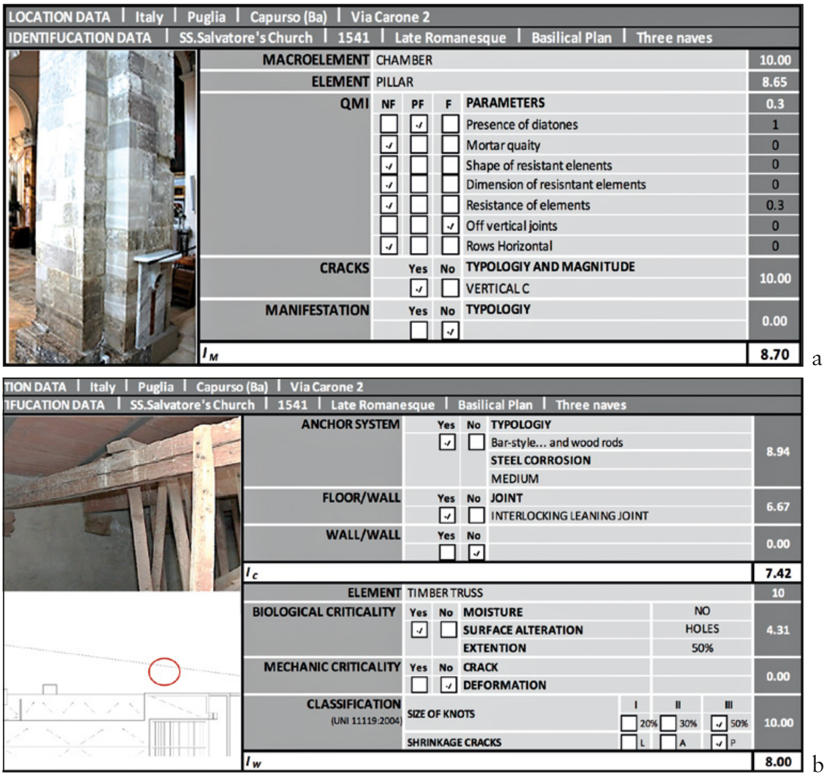


Fig. 5 – Survey forms: a) damaged pillar; b) damaged connection system.

5. Case study

The case study of the SS. Salvatore's church has been selected among the sets of masonry buildings of Bari (Italy), as a representative example of the typical Apulian architectural style in order to apply the proposed methodology. The church is located in the center of Capurso, a town a few kilometers far from Bari. It was built by the will of the queen Sforza in 1541. Its basilical plan, composed by three naves, a transept, an apse, a dome and a bell tower, represents the typical Romanesque architectural style. In order to investigate every aspect of the construction and quantify the criticality of the SS. Salvatore's church, the novel procedure based on the AHP approach has been applied. In particular, the Survey form has been employed. Fig. 5 shows examples of the application of the Survey form respectively for the diagnostics of a pillar (a) located in the church chamber and the connection system of the bearing structure (b) of the lateral transept vault.

Fig. 6 – Longitudinal section with cracks survey.

Finally, the global index is evaluated by considering all the components of the structure. The global index, $I_{STRUCTURE}$ results equal to 1.52. This index points out that the global structural condition is good and only few damages occur on the church. Nevertheless, the damages measured by the Survey forms may be serious. More in-depth investigations are needed as suggested by the I_M (Fig. 5a) and I_C (Fig. 5b) that reach values higher than 7 in a range between 0 and 10.

6. Validation

In order to validate the proposed approach, the AHP-based Condition Rating is compared with the result of a traditional survey and diagnostics approach (Sangiorgio *et al.* 2016a, b). In particular, some specialists carried out a report about the damage state of the SS. Salvatore's church without knowing the innovative procedure (or the results of the procedure) presented in this work (Fig. 6).

The comparison between the results obtained by the application of the proposed methodology and the specialist reports highlights the correspondence of the diagnosis. All the worst pathologies reported trough the Survey forms and quantified by the AHP approach are the same of the damages individuated in the traditional survey. Despite the results similarity, the AHP approach has the advantage to provide a numerical quantification of the criticalities, useful to compare damaged elements of the same structure or identify, on a large scale, the buildings most at risk (Sangiorgio *et al.* 2016a, b).

7. Conclusion

This paper presents a new procedure based on the Analytic Hierarchy Processes (AHP) developed to perform a rapid visual survey and diagnostics of masonry building through a set of condition ratings. Such approach can be easily implemented with information technologies. In particular, in this work the architecture of a DSS supported by an AHP-based diagnostic approach is specified. This methodology provides four innovative aspects in the masonry structure visual diagnostics. Firstly, AHP allows to include qualitative and quantitative data in the analysis. Secondly, the proposed survey and diagnostics performed by suitable condition ratings ensures an extensive application in order to identify the most damaged churches that require more detailed structural investigations. Thirdly the AHP-based diagnostics is combined with a DSS procedure to obtain a powerful tool able to perform analysis at the regional scale. Finally, a comparison with a standard survey is performed to validate the procedure and emphasize the advantages of the novel diagnostics. In the case of regional scale application, such a procedure can be effectively implemented in APP for smart devices and applied for a rapid detection of a large number of buildings and identify a priority list for in-depth investigation.

After discussing the method, a representative case study has been selected in order to validate the proposed method. The results show that the novel approaches provide reliable results and has the advantage of outcoming numerical values to characterize the performance of the structure. Hence, the proposed visual survey-based system, merged with the new IoT technologies, represents a promising tool that, using limited resources, performs the structural monitoring and diagnosis. Future research will provide a large-scale application of the proposed methodology to show the potential of the proposed Decision Support System for the masonry structures monitoring and diagnostics.

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ABSTRACT

Surveys conducted in the aftermath of recent earthquakes have shown that the structural and anti-seismic performances of historical masonry churches are related not only to structural damages and masonry quality but also to other key features such as effectiveness of connections, damages of wooden elements or criticalities related to humidity. Technical and scientific communities are interested in developing or improving existing procedures for the fast-visual survey and diagnostics in order to measure and analyze all the parameters affecting the building performance. In this paper a new procedure, that can be implemented in a Decision Support System (DSS) based on the Analytic Hierarchy Processes (AHP), is developed to perform a rapid visual survey and diagnostics of masonry building through a set of condition ratings. The originality of the presented work is fourfold: 1) the AHP allows to include in the analysis qualitative and quantitative data such as the quality of masonry and connections effectiveness; 2) the proposed survey and diagnostics performed by suitable condition ratings allow an extensive application in order to identify the most damaged buildings that require more detailed structural investigations; 3) the proposed AHP-based approach is integrated in a DSS to provide a powerful computerized tool, useful to large scale data acquisition; 4) the comparison with a standard diagnostics is performed to validate the procedure and emphasize the advantages of the novel diagnostics.