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Structural degradation measurement and diagnostics of historical masonry buildings.

Sangiorgio Valentino[1], Martiradonna Silvia[2], Fatiguso Fabio[3], Uva Giuseppina[4]

[1] *Politecnico di Bari, Dept. DICATECh, Via Orabona 4 Bari 70128 valentino.sangiorgio@poliba.it*
[2] *Politecnico di Bari, Dept. DICATECh, Via Orabona 4 Bari 70128 e Universidad de Cantabria, Dept. Ingeniería Estructural y Mecánica, Av. de los Castros 44 Santander 39005, Spain silvia.martiradonna@poliba.it*
[3] *Politecnico di Bari, Dept. DICATECh, Via Orabona 4 Bari 70128 fabio.fatiguso@poliba.it*
[4] *Politecnico di Bari, Dept. DICATECh, Via Orabona 4 Bari 70128 giuseppina.uva@poliba.it*

Abstract **– Surveys performed in the aftermath of recent earthquakes have shown that the structural and anti-seismic performances of masonry buildings are related not only to structural damages and masonry quality but also other key features such as effectiveness of connections, damages of wooden elements or criticalities related with humidity. To this aim technical and scientific communities are interested in development or improve 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 based on the Analytic Hierarchy Processes (AHP) is developed to perform a rapid visual surveys and diagnostics of masonry building through a set of condition ratings. The novelty of the presented work is threefold: i) the AHP allows to include qualitative and quantitative data in the analysis such as the quality of masonry and connections effectiveness; ii) the proposed survey and diagnostics performed by suitable condition ratings allows an extensive application in order to identify the most damaged buildings that require more detailed structural investigations; iii) a comparison with a standard diagnostics is performed to validate the procedure and emphasize the advantages of the novel diagnostics.

I. INTRODUCTION

The structural diagnostics of a masonry building should take in to account many criteria, phenomena and problems. The process of knowledge starts from an in-depth investigation to consider different aspects of the construction: the building history (expansion interventions, transformations, traumatic events), the geometry, the used technology), the characteristics of the materials and their degradation, cracks and deformation. The synthesis of this information makes possible to understand the structural behavior and formulate an effective diagnosis to highlights the potential weakness, collapse mechanisms, instability and degradation.

In particular masonry churches represent a particularly vulnerable building typology. As some recent catastrophic events pointed out the main critical damage and collapse occurs in structures strongly degraded mainly due to previous historical earthquakes that compromised building structural performance [1]. In this work, the Analytic Hierarchy Process (AHP) [2] is used to study in deep the characteristics involved in the masonry structures performances and set 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 the building. In this field, the use of AHP can be particular effective in order to consider qualitative and quantitative data and analyze the complex problem through a multi-criteria analysis. The resulting condition ratings can be easily implemented in Decision Support System (DSS), an information system that supports maintenance and monitoring decision-making activities [3].

II. AHP BASED METHODOLOGY

The AHP methodology used to quantify the weights of the macro-element collapse modes is based on the well-known Saaty 3-steps Method [2]: i) hierarchical *structuring the problem*, ii) *weight evaluation,* iii) *summary of priority*. Starting from a decision problem, the **first step** consists in *structuring the problem* according to a hierarchical scheme, so to provide a detailed, simple and systematic decomposition of the problem into its basic components. To this aim, the goal of the AHP is identified and the related criteria, sub-criteria and alternatives to reach the goal are determined.

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

Fig.1. The generic matrix of judgments A

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 (Table 1). The result is a *nxn* judgments matrix A (Fig. 1).

Table 1. Fundamental scale of Saaty

a_{ij}	Verbal scale
$a_{ij} = 1$	Equal importance
$a_{ij} = 3$	Moderate importance of one over another
$a_{ij} = 5$	Strong importance
$a_{ij} = 7$	Very strong importance
$a_{ij} = 9$	Extreme importance
1.5 - 4 - 6 - 8	Intermediate value
1/9,1/8,….,1/2	The reciprocal expresses an opposite judgement

Solving an eigenvector problem [2], 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) and its expected value denoted as Random Index (RI) from which the Consistency Ratio (CR) is obtainable. [2]

Among the different values of *RI* proposed in the related literature, the values of Noble [4] is used and reported in Table 2. On the basis of several empirical studies, Saaty concluded that the value of Consistency Ratio CR< 0.10 is acceptable [2].

The **third step**, i.e., the *summary of priority,* is performed to determine the global ranking and the global weights: to this aim the weights of each criterion are combined with the weights of the alternatives. Such a global weight is obtained by multiplying each criteria weight to the alternative weight and by summing the results for each alternative.

Table 2. Random consistency index of Noble [4]

n	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	*0.49*	*0.82*	*1.03*	*1.16*	*1.25*	*1.31*	*1.36*	*1.39*

III. AHP APPLICATION

A. *Step 1: the problem of the masonry damage and quality*

The first step in AHP, as applied to the evaluation of the loss of masonry structural performances due to many typologies of construction criticalities and damages.

This analysis is particularly effective to take into account all the aspects involved in the structure diagnostics and to have an exhaustive overview of the possible problems affecting a masonry churches.

The first macro-criterion to determine structure performances regards the quality of the masonry.

Five criteria are considered and showed in Fig. 2.

The first criterion classifies the macro elements of the churches by considering the recurrent failure mechanisms. The macro elements are listed as follows: chamber, façade, chapel, roof, transept, apse, bell tower, dome and triumphal arches (indicated in blue in Fig. 2).

The second criterion regards the damaged elements. It is worth noting that recent post-earthquake observations in Italy (i.e. Umbria and Marche, 1997; L'Aquila, 2009; Emilia, 2012; Central Italy, 2016) shows different levels of vulnerability depending on the damaged building components [1,5]. The Elements criterion consider the possible masonry components: wall, pillar, column, arch, vault, architrave, floor strips and ribs.

The third fundamental criterion exploits an existing methodology called Masonry Quality Index (*MQI)* method. This method is particular effective and perfectly compatible with the AHP. To this aim, such method is exploited and incorporated in the AHP methodology. *MQI* method consists in evaluating the presence, the partial presence, or the absence of certain parameters that define the "rule of the art", namely a set of construction devices that, if executed during the construction of a wall, provides a good behavior and ensure the compactness and the monolithic quality [6] In such approach a visual procedure is used to classify the masonry on the base of a set of parameters (stone properties SM, stone dimensions SD, stone shape SS, wall leaf connections WC, Horizontal bed joint HJ, vertical joints VJ, mechanical properties MM) and finally the *MQI* is evaluated through tabulated values . The fourth criterion is related with the masonry performances regards cracks or criticality manifestation affecting the building. To this aim it is necessary take into account the type of damaged element in order to perform an exhaustive AHP and diagnostics. In addition, the classification of the damages is set according to a well-acknowledged classification model [7].

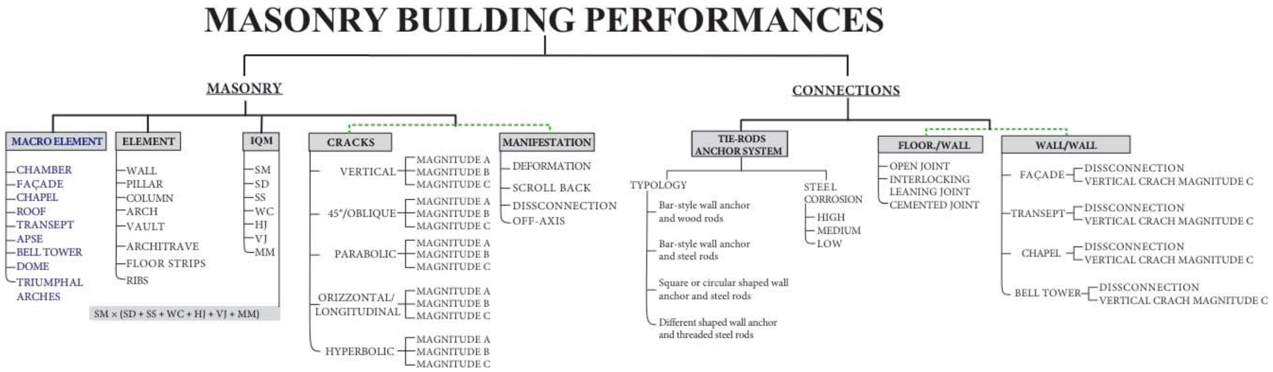

Fig.2. Structure of the Problem: Masonry diagnostics

In this approach, the building damages 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, also the criterion criticality Manifestation is considered by identifying any deformation, Scroll back, disconnection or scroll backs.

The second macro-criterion is the consider the efficiency of wall-to-floor and wall-to-wall connections, since they assure the continuity of the energy path and prevent the occurrence of most of the local collapse mechanisms. In fact, out-of-plane behavior of masonry walls observed in recent seismic events showed the critical importance of proper connections in historical buildings.

B. Step 2: weight evaluation

The second step in the AHP individually analyses each aspect of the Structure of the Problem in order to weight criteria and parameters involved.

This Section exploits previous studies regarding every aspect involved 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.

The weight calculations of the tie road anchor system related to the Connections macro criterion is showed. The Tie-Roads effectiveness is related by the typology (classified by year of manufacture) and the level of steel corrosion as discussed in the structuring of the problem. Starting to the typology, pairwise comparisons of the alternatives are carried out performing a qualitative analysis to achieve the judgment matrix. The weights were obtained by solving the eigenvector problem, as shown in Eq. (1).

Table 3. Judgment Matrix for the typology parameter, weights, and CR

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

The resulting matrix satisfied the Consistency Ratio requirement CR<0.1 and it is possible derive consistent weights, normalized between 0 and 1 (see Table 3).

The second parameter is the steel corrosion that is classified such as low medium or high in the structuring of the problem. A qualitative evaluation is performed to quantify the influences of the corrosion on the Tie-Roads performance basing on detailed studies present in related literature.

C. 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 sub-criteria weight and adding the results, as in the classical AHP procedure. To this aim two condition ratings are defined: *Masonry Index* (I_M) and *Connection Index* (I_C).

To provide an example, the I_M can be obtained 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 obtained with the matrices of comparison.

Criterion	CONNECTIONS							
Sub-criterion	TIE-RODS TYPOLOGY	v_6	TIE-RODS STEEL CORROSION	v_7	FLOOR/WALL	v_8	WALL/WALL	v_9
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

Let it assume to have surveyed a component of the Building, 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, [8]:

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

Where v_i are the sub-criterion and $w_{i,j}$ are the parameters of the analysis.

Analogously it is possible to evaluate the performances of *Connection*. The *Connection Index (I_C)* is evaluated by the following formula:

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

Finally, the global condition rating (*global index* $I_{STRUCTURE}$) is evaluated a weighted average of the I_M and I_C, evaluated for all the components of the structure (Sangiorgio et al 2018a, 2018b).

IV. CASE STUDY

A. Survey form

In order to perform the diagnostics, suitable survey forms are developed to acquire all the necessary information.

Such survey forms can be implemented in smart devices and outcomes the condition ratings by exploiting equations (5-6). Such form can be performed for any damaged or degraded element of the structure to obtain the numerical evaluation of its condition by taking into account all the macro-criteria, criteria and sub-criteria of the considered AHP problem.

B. Case study

In order to apply the proposed methodology, among the sets of masonry buildings of Bari (Italy), the case study of the church "SS. Salvatore", has been selected because it exhibits a typical structural construction style in Puglia.

The Church of SS. Salvatore's is in the center of Capurso, a town located few kilometers from Bari. It was built by the will of the queen Sforza at 1541 with late Romanesque architectural style. It is composed of three naves, the central one wider than the others, of a transept, an apse, a dome and a bell tower. The most important recent modification was the substitution of the wood roof of the principal nave with a heavy reinforced concrete one. The novel procedure based on the Analytic Hierarchy Processes (AHP) is applied on the "SS. Salvatore's" church, in particular, the survey forms are applied to analyze every aspect of the construction and quantify every criticality. Fig. 4, 5 show examples of the application of the Survey form respectively for the diagnostics of a pillar located in the church chamber and the connection system of the bearing structure of the lateral transept vault.

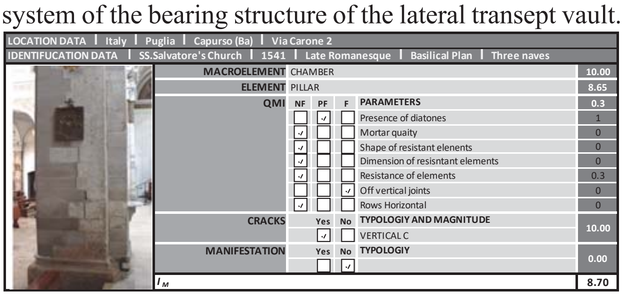

Fig.4. Survey forms: damaged Pillar

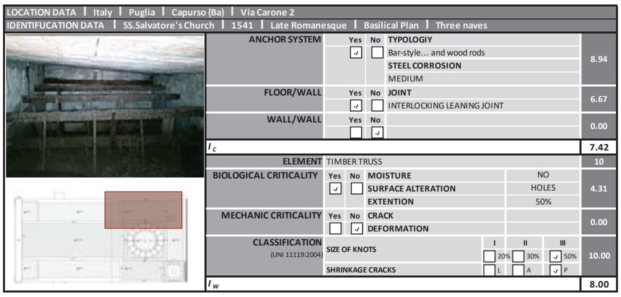

Fig.5. Survey forms: damaged connection system

Finally, the global index is evaluated by considering all the components of the structure. The global index, $I_{STRUCTURE}$ results equal to 1.52 in a scale between 0 and 10. This index points out that the overall structural condition is good and only few damages occur on the Church. On the other hand, the few damages surveyed by the survey forms may be serious. More in-depth investigations are needed as suggested by the I_M (Fig. 4) and I_C (Fig. 5) that reach values higher than 7 in a range between 0 and 10.

V. VALIDATION

In order to validate the proposed approach for the Romanesque masonry church, it is necessary to compare the Condition Ratings attained through the proposed methodology with the result of a traditional survey and diagnostics approach [9-10]. In particular, some specialists, who didn't know the values obtained by the innovative approach, carried out a report on the damage state of the "SS.Salvatore's" Church. They performed a direct on-site inspection; the technical drawings of the church including the surveyed criticalities and wrote a report.

The experts highlighted that the pillars near to the dome present the worst cracks and deformations, probably caused by the heavy weight of the reinforced concrete roof covering the central nave. Hence, they deduced that these structures are affected by compression damage.

In the technical sheets, that include significant transverse sections, e.g. in Fig. 6, the cracks are highlighted with the red color and clearly show the serious damage of the pillars.

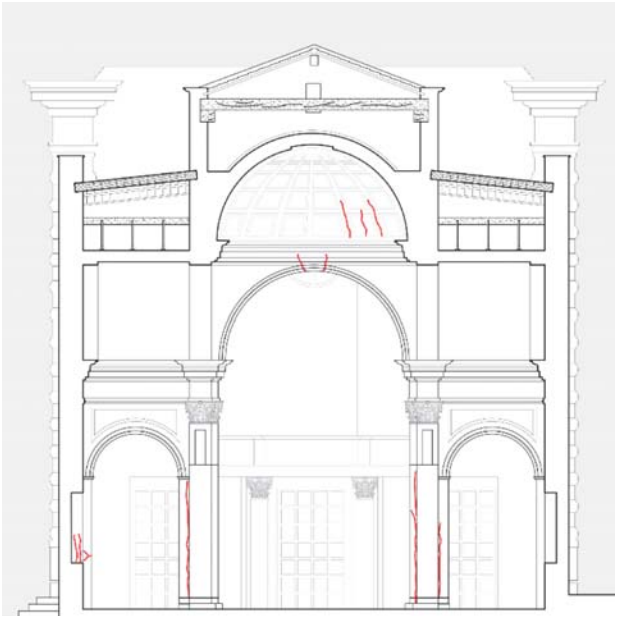

Fig.6. Transverse section with cracks survey

The comparison between the results obtained by the proposed methodology application and specialist report, remarks the correspondence of the diagnosis. All the worst pathologies reported trough the Surveys forms and quantified by the AHP approach agree with the damages individuated from the traditional survey. Moreover, also the minor degradation phenomena in the remaining structures are comparable. Despite the results similarity, the AHP approach has the advantage of output a numerical quantification of the criticality, useful to compare damaged elements of the same structure or identify, on a large scale, the buildings most at risk.

Furthermore, it allows comparing different damages on the same structure and providing the support to plan more in-depth surveys as e.g. destructive investigations.

Finally, such approach can be implemented in smart devices and information platform to the large-scale application [11]. In this field the specified condition ratings assume a fundamental role to perform the comparison among different building structures and typologies.

VI. CONCLUSION

This paper presents a new procedure based on the Analytic Hierarchy Processes (AHP) developed to perform a rapid visual surveys and diagnostics of masonry building through a set of condition ratings. In particular, this methodology provides three innovative aspect in the masonry structure visual diagnostics. Firstly, the AHP allows to include qualitative and quantitative data in the analysis including connections, wooden elements and humidity. Secondly, the proposed survey and diagnostics performed by suitable condition ratings allows an extensive application in order to identify the most damaged buildings that require more detailed structural investigations. Thirdly, 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 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 suitable case study has been selected in order to assess the proposed methodology. Among the sets of masonry churches of Bari (Italy), the "SS. Salvatore's" church has been selected because it exhibits a typical and widespread structural construction style in Puglia. The validation of the method has been performed by comparing the defined Condition Ratings with the result of a traditional survey and diagnostics approach. The results show that the system obtains reliable results and has the advantage of outcoming numerical values to characterize the performance of the building. Hence, the presented visual survey-based system, combined with the new IoT technologies, represents a promising tool for the monitoring and diagnostic by using limited resources.

Future research will provide a large-scale application of the proposed methodology by developing an exhaustive Decision Support System for the masonry structures monitoring and diagnostics.

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