IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Lecce, Italy, October 23-25, 2017

Structural vulnerability assessment of masonry churches supported by user-reported data

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***Abstract* – Ancient masonry churches represent a particularly vulnerable architectural typology, and the experience progressively acquired during post–earthquake surveys has pointed out that recurrent damage patterns and main failure mechanisms can be identified and studied by separately looking at the different architectural "macro–elements": façade, nave, aisle, transept, lateral chapel, dome, bell tower.**

In the last few years, the macro-element approach has been extensively and fruitfully applied to perform preliminary vulnerability assessments, by recognizing the correspondence between each structural macro-element and the most recurrent collapse mechanisms associated. This type of approach has been also incorporated in the Italian Guidelines for the seismic vulnerability analysis architectural heritage.

In the paper, the above-mentioned method is applied by a Multi-Criteria Decision Analysis approach designed for the support of decisions involving expert judgements and several alternatives. The peculiarity of the system is the retrieval of additional data by a User-reporting Application. In the specific case of masonry churches, the application involves the integration of these data in the vulnerability macro-element approach.

I. INTRODUCTION

The protection of historical and cultural architectural heritage against seismic hazard is a topic that has deserved a major attention in Italy in the last decades. The recent post-earthquake observations in Italy (i.e. Umbria and Marche, 1997; L'Aquila, 2009; Emilia, 2012; Central Italy, 2016) show that the question is still open [1] and there is the need of further developing research studies aimed at the assessment of the existing building stock at the regional scale [2, 3, 4] but also of improving methods and effective computational tools for the assessment of single monuments by properly accounting for the complex nonlinear behavior of masonry monuments under seismic events [5, 6].

Prevention is of course a crucial node, especially in the case of monuments and historical buildings, for which physical damage corresponds to an irreparable cultural, intangible wound. In these cases, post-damage retrofit often has no meaning, since the architectural and artistic value is lost, but it is rather necessary to perform an effective monitoring of the actual structural vulnerability and ongoing degradation, in order to promptly detect critical situations and implement retrofitting provisions able to mitigate risk.

In this paper, attention is focused on historical masonry churches, which represent a particularly vulnerable architectural typology. The experience progressively acquired during post-earthquakes surveys and the consequent research studies have revealed that recurrent damage patterns and failure mechanisms can be identified, leading to the idea that it is possible to separately investigate the different architectural "macro–elements": façade, nave, aisle, transept, lateral chapel, dome, bell tower, … [7, 8], as sketched in Figure 1.

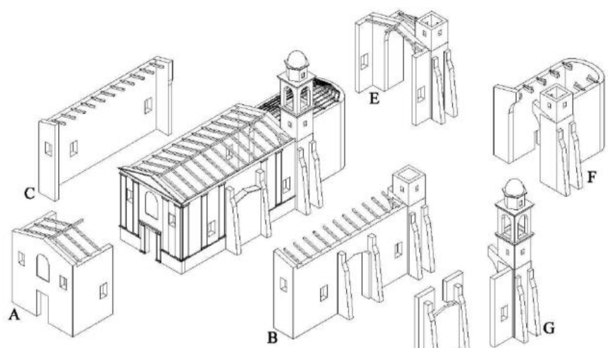

Fig.1. Schematic representation of the macro–elements of a typical historical church.

Thus, it has become an accepted practice to evaluate the seismic response of limited structural parts and macro-elements instead of considering the complete building at one time. This type of approach, which is incorporated in the Italian Guidelines for the Seismic

Risk Assessment of the Architectural Heritage [9], has been usefully applied to perform preliminary vulnerability assessment, by recognizing the association between each structural macro-element typology and the most recurrent collapse mechanisms, based on a relatively large amount of available data [10, 11], and also for performing more detailed vulnerability assessment individual buildings [12, 13, 14].

This paper is focused on the vulnerability assessment at the regional scale of historical masonry churches by a synthetic *Index of Vulnerability* based on 1st and 2nd level vulnerability forms, developed in Italy since 1987 [9, 15, 16]. In particular, the formulation of the method is improved by an Analytic Hierarchy Process (AHP) able to calibrate the relative importance of the kinematic and static criteria and automatically assign the weight to each mechanism. Moreover, it is outlined the incorporation of the vulnerability assessment within the more general framework of a *Quality Detection Platform (QDP)*, supported by a specific Information System and an APP for the integration of User-reported information.

II. OVERVIEW ABOUT SIMPLIFIED METHODS FOR THE VULNERABILITY ASSESSMENT OF CHURCHES

In order to quantify the vulnerability of churches at a regional scale and provide a rational basis for risk mitigation plans, it is fundamental to define simplified methods able to provide extensive information on a large portfolio of buildings and, at the same time, reduce the cost and time of field investigation. In Italy, the first simplified method provided for the churches vulnerability analysis was the "GNDT – S3 Model" sheet (1987), based on subdivision of structure in macroelements. In the following years, after the experience gained after many Italian Earthquakes the sheet was modified and updated to the latest version, in which the vulnerability evaluation is based on 28 damage mechanisms [9, 15, 16] that can be activated on specific macro-elements (Fig. 1). According to this simplified approach, which can be classified within the framework of indirect vulnerability methods, the building performance is expressed via a *Vulnerability Index* i_v [9, 15, 16, 17] that summarizes the constructive characteristics and quality (considering also a-seismic devices) that can directly influence the collapse mechanisms of the building, contrasting or favouring their activation. It is defined as a weighted average of the vulnerability of each macro-element:

$$i_v = \frac{1}{6}\frac{\sum_{k=1}^{28}\rho_k\,(v_{ki} - v_{kp})}{\sum_{k=1}^{28}\rho_k} + \frac{1}{2} \qquad (1)$$

For the generic mechanism k ($1 \leq k \leq 28$), ρ_k is the weight assigned to the mechanism and represents the influence of each mechanism in the global behaviour of structure and is variable from 0.5 to 1 according to predefined ranges. v_{ki} and v_{kp} are respectively the vulnerability score and the a-seismic score of the macro-element, and are variable from 1 to 3. All these values are evaluated on the base of the experience of the surveyors. The maximum vulnerability level corresponds to $i_v = 1$.

The application of the procedure on a portfolio of church in a specific geographic area allows to determine a mean vulnerability index $i_{v,m}$, which is a significant synthetic indicator of the mean vulnerability of a representative sample and can provide useful indications for damage scenarios and mitigation strategies [10, 11].

Although Eq.1 is very widespread and widely accepted in the study of churches' vulnerability, it is worth noting that it is strongly affected by a few uncertainty factors related to the subjective opinion of surveyors, who autonomously assign a score to each mechanism (both on the vulnerability score and the a-seismic score of each mechanism) basing on their personal judgement and experience. The definition of ρ_k is an additional uncertainty factor, which can provide an unrealistic vulnerability index.

In the present work, in order to reduce, at least in part, the aforementioned issues, the values of ρ_k are redefined according to a novel classification of the mechanisms, proposed by the authors, based on the recognition of the structural hierarchy among macroelements. A Multi-Criteria Decision Method called Analytic Hierarchy Process [18] is applied in order to evaluate fixed values of ρk through the weighting of kinematic and static criteria.

III. 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 [18]: 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.2. 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 analyse each aspect of the decision problem. Considering *n* ordered criteria of comparison (i.e., criteria, sub-criteria or alternatives in relation with criteria or sub-criteria), a $n \times n$ *judgments matrix A* is defined (Fig. 2), where each upper diagonal element $a_{ij}>0$ is generated by comparing the *i*-th element with the *j*-th one through the fundamental scale of absolute numbers (Table 1). This semantic scale is composed by verbal scales that are associated to numerical values (1, 3, 5, 7, 9) and compromises (1.5, 2, 4, 6, 8) between them.

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

The AHP uses the principal eigenvalue method for deriving ratio scale priority vectors from positive reciprocal matrices. The weights are obtained by solving the following eigenvector problem:

$$A\ w = \lambda_{max}\ w \qquad (2)$$

where *w* is the eigenvector and λ_{max} is the principal eigenvalue. In addition, Saaty defines the consistency index *CI* to check the coherence of the assigned judgement. Such index increases proportionally with the incoherence of the matrix:

$$CI = \frac{\lambda_{max}-n}{n-1} \qquad (3)$$

Operationally, to verify that the paired comparisons are coherent and the result is reliable, the consistency test is performed trough the *Consistency Ratio* (*CR*). More precisely, *CR* is obtained by considering the ratio between *CI* and its expected value denoted Random Index (*RI*) determined over a large number of positive reciprocal matrices of order *n* whose entries are randomly chosen in the set of values $n \in \{1,2,..., 20\}$. The following relationship holds:

$$CR = CI/RI(\text{n}). \qquad (4)$$

Among the different values of *RI* proposed in the related literature, the values of Noble [19] 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 [18].

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 [20].

Table 2. Random consistency index of Noble [19]

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*

IV. APPLICATION OF AHP METHODOLOGY ON MECHANISM WHEIGT DEFINITION

The definition of parameters in Eq.1 is the crucial node in the computation of the Vulnerability Index i_v, especially in the phase of score assignment, where uncertainty sources can introduce significant errors. In the proposal presented in the paper, instead of demanding the values of ρ_k to the human choice, they are univocally assigned through the application of the 3-steps AHP methodology, as follows [21-23].

In the **first step**, the *problem* (i.e. the classification of the collapse mechanisms involved in the vulnerability assessment) *is structured according to a hierarchical scheme*. To this aim, 3 criteria are defined in accordance with hierarchy strength principles: i) *Element typology*; ii) modality of *Failure mechanism*; iii) *Damage typology*. In addition, for each criterion, a set of *j* alternative are defined. Figure 3 shows the hierarchical scheme of the decision problem.

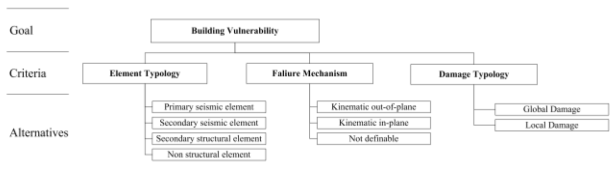

Fig.3. Problem structuring in a hierarchical scheme

The **second step** of AHP provides the weights, which are defined as follows:

- v_i is the weight associated to *i*-th criterion;
- w_{ij} is the weight associated to *j*-th alternative with respect to *i*-th criterion. The step 2 is performed to obtain four *judgments matrix A*: three matrices to identify the weights of alternatives w_{ij} and one to identify the weight of each criterion v_i.

Element typology	Pse	Sse	Se	Nse	*CR*	W_{1j}
Primary seismic element (Pse)	1	2	4	9		1.00
Secondary seismic element (Sse)	0.5	1	2	6	0.004	0.76
Secondary structural element (Se)	0.25	0.50	1	3		0.63
Non structural element (Nse)	0.11	0.16	0.33	1		0.54

Fig.4. Matrix of element typology, CR and weights

For the sake of brevity, only the matrix for the *element typology* is shown in Fig. 4. In such a matrix, values have been assigned by experts by performing a pairwise comparisons of the involved alternatives. The resulting matrix satisfies the Consistency Ratio requirement *CR*<0.1 and allows to derive coherent weights w_{1j}, that have been normalized between 0.5 and 1 in accordance to the original procedure [9, 15, 16, 17].

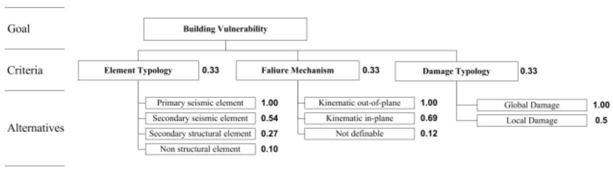

Fig.5. Problem structuring and resulting weights

Figure 5 shows all the weights for each criterion and the alternatives evaluated in step 2, as represented in the hierarchical scheme.

Table 3. Weights obtained by AHP for each collapse mechanisms

k	COLLAPSE MECHANISM	ρ_k
1	FAÇADE OVERTURNING	*1.00*
2	TYMPANUM OVERTURNING	*0.92*
3	IN PLANE MECHANISMS OF FAÇADE	*0.95*
4	NARTHEX	*0.65*
5	TRANSVERSAL RESPONSE OF THE NAVE	*0.92*
6	SHEAR MECHANISM OF LATERAL WALLS	*0.95*
7	LONGITUDINAL RESPONSE OF COLONNADE	*0.95*
8	VAULTS OF CENTRAL NAVE	*0.87*
9	AISLES VAULTS	*0.79*
10	TRANSEPT FAÇADE OVERTURNING	*0.92*
11	SHEAR MECHANISM IN TRANSEPT	*0.87*
12	TRANSEPT VAULT	*0.79*
13	TRIUMPHAL ARCHES	*0.95*
14	DOME	*0.79*
15	ROOF LANTERN	*0.79*
16	APSE OVERTURNING	*0.92*
17	SHEAR MECHANISM IN THE APSE	*0.87*
18	APSE VAULTS	*0.79*
19	ROOF OF THE NAVE	*0.92*
20	ROOF OF TRANSEPT	*0.84*
21	ROOF OF APSE	*0.84*
22	CHAPEL OVERTURNING	*0.84*
23	SHEAR MECHANISM IN CHAPELS	*0.79*
24	CHAPEL VAULTS	*0,79*
25	IRREGULARITY IN PLAN/ELEVATION	*1.00*
26	ARCHITECTURAL PARTS	*0.77*
27	BELL TOWER	*1.00*
28	BELFRY	*0.72*

Once the weighting is performed for all criteria and alternatives, it is possible to re-calculate ρ_k according to the AHP classification of the collapse mechanisms. Such operation coincides with the **third step** of the *summary of priority*. Each weight ρ_k of the single k-th mechanism can be evaluated as a combination of the weighted criteria alternatives, as follows:

$$\rho_k = v_1 w_{1j} + v_2 w_{2j} + v_3 w_{3j} \qquad (5)$$

To provide an example, with reference to the mechanism of façade overturning, k=1 since the element is seismic and primary, the kinematic is out of plane and the damage is global. Equation (5) then provides:

$$\rho_1 = 0.33{*}1 + 0.33{*}1 + 0.33{*}1 = 1$$

All the ρ_k weights, with k=1…28, can be evaluated by Eq. (5), and are shown in Table 3.

V. CASE STUDY

In this section, an application of the newly proposed procedure is shown for two case study in the Province of Alessandria - Piemonte:

1) Church of San Nicolò, Novi Ligure (B1);
2) Church of Sant'Eusebio, Carezzano Maggiore (B2).

Both buildings are masonry churches, as shown in Figures 6 and 7.

Fig. 6. Church of S. Nicolò, Novi Ligure.

Fig. 7. Church of Sant'Eusebio, Carezzano Maggiore

The masonry church of S. Nicolò in Novi Ligure was built in 12th century, and retrofitted starting from 1682, for 20 years. The building is a perfect example of Baroque architectural style, with elliptical-rectangular plant, with dimensions of *25 m x 50 m*. It presents a unique nave, a semicircular apse under a cupola and 10 lateral chapels. Outside, the church is completely constituted by solid bricks, and it presents a pitched roof made with ceramic tiles.

The masonry church of S. Eusebio in Carezzano

Maggiore was built in 16th century, with elliptical-rectangular plant. It is constituted by a central nave, a semicircular apse and two lateral chapels. Starting from the first years of 20th century, retrofit actions were taken. In particular, in 1912 the vault over the altar was substituted by a slab made with steel beams, whereas in 1977 the apse masonry was reinforced with concrete and the foundation was retrofit with rc beams.

For both cases, during an on-place survey v_{ki} and v_{kp} have been evaluated by following the classical procedure [9], and ρ_k have been evaluated based on the experience of the surveyor. Finally, i_v has been calculated through Eq. 1. The proposed procedure has been then applied, directly obtaining through the AHP the values of ρ_k, which are therefore fixed and independent from the surveyor's judgement.

Table 4. Score assignment for B1

Collapse mechanism *k*	v_{kp}	v_{ki}	ρ_k (classic)	ρ_k (proposed)
3	*0*	*2*	*1*	*0,95*
5	*3*	*2*	*1*	*0,92*
6	*0*	*1*	*1*	*0,95*
8	*3*	*2*	*1*	*0,87*
10	*2*	*0*	*0,5*	*0,92*
12	*0*	*1*	*0,5*	*0,79*
13	*2*	*2*	*1*	*0,95*
16	*2*	*2*	*1*	*0,92*
17	*0*	*2*	*1*	*0,87*
18	*2*	*2*	*1*	*0,79*
19	*0*	*2*	*1*	*0,92*
20	*0*	*2*	*0,5*	*0,84*
21	*0*	*2*	*1*	*0,84*
25	*0*	*2*	*1*	*1,00*
26	*1*	*1*	*0,8*	*0,77*
27	*1*	*2*	*1*	*1,00*
28	*2*	*2*	*1*	*0,72*

Table 5. Score assignment for B2

Collapse mechanism k	v_{kp}	v_{ki}	ρ_k (classic)	ρ_k (proposed)
1	*2*	*2*	*1*	*1,00*
2	*0*	*1*	*1*	*0,92*
3	*0*	*1*	*1*	*0,95*
5	*3*	*2*	*1*	*0,92*
6	*3*	*0*	*1*	*0,95*
8	*2*	*1*	*1*	*0,87*
13	*3*	*0*	*1*	*0,95*
16	*0*	*1*	*1*	*0,92*
17	*3*	*1*	*1*	*0,87*
18	*0*	*1*	*0,5*	*0,79*
19	*2*	*1*	*1*	*0,92*
21	*0*	*1*	*1*	*0,84*
22	*0*	*1*	*0,5*	*0,84*
23	*3*	*2*	*0,5*	*0,79*
26	*0*	*2*	*0,8*	*0,77*
27	*0*	*2*	*1*	*1,00*
28	*0*	*1*	*1*	*0,72*

The results of the classical and new procedure are compared in Table 4 and 5 for B1 and B2 in terms of vulnerability scores and ρ_k. In particular, such tables show the values assigned by surveyors "*ρ_k (classic)*" and the values *"ρ_k (proposed)"* assigned by using the proposed AHP procedure. From the application of Eq. 1 by using the values of Tables 3 and 4, the following results are obtained:

B1: $i_v = 0.607$; $i_{v,proposed} = 0.611$
B2: $i_v = 0.481$; $i_{v,proposed} = 0.484$

The resulting values of i_v obtained are similar, but the results of the proposed methodology are exempt from subjective judgments related to the severity of the mechanism.

CONCLUSIONS

Simplified approaches of vulnerability analysis on large scale are increasingly used for the assessment of the architectural heritage. In the last decades, the scientific and technical communities have been deeply committed in studying and improving the reliability of the such methodologies.

This paper proposes an improvement of the indirect methods for the preliminary vulnerability assessment of historical masonry churches based on the macro-element approach and compilation of quick vulnerability sheets by thanks to the application of a Multi-Criteria Decision Analysis. An Analytic Hierarchy Process involving expert judgements and several alternatives is applied in order to directly quantify the weights applied to the different potential mechanisms used in the formulation of "GNDT – model S3". The main steps of the AHP to perform weighting are explained and applied to the case of the 28 possible macro-element kinematics of the masonry churches. To this aim, the correspondence between each structural macro-element and the most recurrent collapse mechanism is examined. Two case studies are developed to compare the vulnerability index obtained by using the new weights with those provided by the classic procedure. The resulting vulnerability is similar for both methodology, even if this result cannot of course be generalized after only 2 case studies, and shall be extensively validated in the future. Anyway, it is worth remarking the novelty of the proposed approach that allows a direct preliminary computation of the weights, reducing the subjectivity of the analysis. In addition, the methodology shows the effectiveness of Multi-Criteria Decision Analysis in join qualitative information in the analysis. Future research will provide a formulation integrating other qualitative parameters not currently involved in the standard approach for masonry buildings vulnerability analysis thanks to the incorporation of the procedure within a more general Quality Detection Platform including data reported by users by a specific APP.

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