

Article

Protection of Cultural Heritage Buildings and Artistic Assets from Seismic Hazard: A Hierarchical Approach

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Received: 15 December 2019; Accepted: 12 February 2020; Published: 21 February 2020



Abstract: The occurrence of natural disasters such as earthquakes represent a worldwide challenge in the conservation of cultural heritage (CH), which suffer from damage due to high vulnerability conditions. Therefore, the protection of CH from seismic hazard is of paramount importance. Damage and vulnerability assessment of CH and artistic assets play a key role in the identification of conservation strategies. Effective strategies require the stabilization of severely damaged buildings and the preventive improvement of constructions structural response to seismic actions. Although the operation of emergency inspections is meant to classify buildings on the basis of buildings residual seismic capacity, investment decisions in restoration and conservation strategies of such vulnerable structures must take into consideration tangible and intangible values of both building structures and artistic goods as well as must combine objectives of verifying structural safety standards and preserving cultural heritage significance. Damage and vulnerability assessment depend on different criteria, which, on the one hand, are related to buildings structural characteristics, materials, and geometrical properties. On the other hand, to the peculiarities and uniqueness of artworks and artistic goods present on structural elements. In this paper, an AHP (absolute) model is proposed to rank multi-criteria prioritization of protection and restoration interventions on a set of 15 churches, which were damaged by earthquakes, occurring in Italy in the last decades. In detail, in order to structure the decision problem, identify key factors, and define the hierarchy, we conducted an extensive literature review and interviewed a pool of experts. Focus groups were organized to develop the set of criteria and sub-criteria and validate the hierarchy by dynamic discussion.

Keywords: cultural heritage; cultural heritage; artistic assets; multicriteria decision aid; AHP; seismic hazard

1. Introduction

The occurrence of natural disasters such as earthquakes represent a worldwide challenge in the conservation of cultural heritage (CH), which suffer from damage due to high vulnerability conditions. Historical city centers are threatened by events referring to natural and anthropic causes, the occurrence of which can lead to important losses in terms of cultural and artistic goods. In such a context, historical masonry buildings constitute the most extended stock of CH, including both the architectural structures and their contained artworks. Masonry buildings are particularly vulnerable to earthquakes as they often present weaknesses due to construction aspects (low quality materials, irregular arrangements, inaccurate architectural details, etc.) and lack of conservation [1,2]. This context also highly jeopardizes the preservation of artistic assets, both movable and unmovable, whose risk is connected not only to intrinsic or typological issues, but also to the behavior of the structural system. The seismic behavior of historical masonry buildings is evaluated by the macro-element approach, i.e., the structural system is

considered composed of independent portions whose limits are identified among either crack patterns or construction/vulnerability defects (e.g., large voids, lack in connections, etc.) [3,4]. Such an approach is particularly effective for churches as macro-elements can also coincide with the architectural portions of the building (apse, façade, dome, etc.), whose brittle behavior has been observed even under earthquakes of moderate magnitude [5,6].

Hence, to face the seismic post-emergency phase [7] a comprehensive methodology able to contribute in managing the protection of both artistic assets and structural issues is needed. Damage and vulnerability assessment of CH and artistic assets plays a key role in the identification of effective conservation strategies, which require the stabilization of severely damaged buildings and the preventive improvement of constructions structural response to seismic actions. Investment decisions in restoration and conservation strategies of such vulnerable structures must take into consideration the tangible and intangible values of both building structures and artistic goods. It must also combine objectives of verifying structural safety standards and preserving CH significance. Protection of CH involves high investment costs, which usually exceeds available financial resources due to stringent budget constraints. It is therefore necessary to prioritize interventions [8–11]. In this context, in which decision-making involves high stakes and stochastic future implications, multicriteria approaches provide formal decision-making techniques to assess a finite set of criteria, evaluate alternatives on the basis of each criterion, and aggregating these evaluations to rank alternatives with respect to a specific objective (e.g., priority of intervention). Among the variety of multicriteria methods provided in literature, the Analytic Hierarchy Process (AHP) proposed by Saaty in the Eighties [12], is one of the most widely used across multiple domain worldwide (e.g., business, social studies, environmental studies, R&D, etc.) in taking complex decisions in real-world situations. Due to its ease of use and understanding, it facilitates structuring the complexity, measurement, and synthesis of rankings [13]. Nonetheless, there are few contributions in literature, to our knowledge, on the implementation of the AHP to the valuation of CH and historic buildings preservation [14–17].

In this paper, a novel application of the AHP in the domain of CH vulnerability assessment is proposed. In detail, we develop and implement an AHP (absolute) model to rank multi-criteria prioritization of protection and restoration interventions on CH, i.e., churches, damaged by earthquakes. Based on literature review and experts' judgements, tangible valuation criteria, sub-criteria, and ratings were identified, and weights were determined by pairwise comparisons of elements with tangible properties to create a one-dimensional index for representing the overall assessment of alternatives, and rank them from most to least vulnerable. Then the model was validated on a set of 15 churches, which were damaged by earthquakes, occurring in Italy in the last decades. These buildings present damage and vulnerability aspects related to structural components and their supported artistic assets, whose data (surveyed on site visual inspections have been collected in a new web archive called DataBAES [18]. Such a tool provides two levels of inspections: the former is limited to damage survey of the artistic asset, such as structural element pairs detected in a building, whereas the latter includes also vulnerability issues of the pairs in questions. Level I and level II survey forms are provided (see supplementary materials in [18] to support the onsite inspections. Therefore, level I corresponds to emergency phases (i.e., when more expeditious survey is in need), whereas level II can be applied in any other phase to deeply clarify the relationships between present vulnerabilities and potential further damage, thus providing useful information for the possible prioritization and identification of interventions.

The remainder of the paper is organized as follows. Section 2 describes materials and method, Section 3 provides the model and presents its implementation on a real-world situation where 15 Italian churches which suffered from damage caused by recent earthquakes in Italy are ranked according to priority of intervention to mitigate seismic hazard, Section 4 discusses results, and finally, Section 5 concludes.

2. Materials and Method

2.1. Materials

A set of 15 churches were selected among the case studies included in the DataBAES web archive [18,19] to validate the proposed AHP model and consequently implement it in the wider context of preservation of historical structures and their integral unmovable artworks (e.g., frescoes and mural paintings, stuccoes, and mosaics). Most of Italian CH assets, specifically churches, were struck by earthquakes along their history and their main characteristics, and in terms of both construction details and possible occurred damage, are taken into consideration in the modeling. Vulnerability is also taken into account (e.g., irregular arrangements, large openings, too slender piers, lack of connections, thrusting arch/roof, etc.), as well as the presence of possible earthquake-proof devices (e.g., ties, confining rings at floor/roof level, etc.). Table 1 lists the buildings examined in the study.

Table 1. Churches under investigation in this study.

Church	Localization (Province)	Reference Earthquake
Chiesa di Sant'Antonio	San Polito Ultra (AV)	1980
Complesso di Santa Maria ai Monti	Tricarico (MT)	1980
Chiesa dell'Annunziata	Laurino (SA)	1980
Chiesa di Santa Maria delle Grazie	Cassano Irpino (AV)	1980
Complesso della Madonna del Carmine	Tricarico (MT)	1980
Chiesa di San Michele Arcangelo	Saviano (NA)	1980
Cappella degli Scrovegni	Padova	-
Chiesa di San Marco	L'Aquila	2009
Chiesa di San Silvestro	L'Aquila	2009
Chiesa del Santo Rosario	Finale Emilia (MO)	2012
Chiesa di S. Egidio	Cavezzo (MO)	2012
Chiesa dei Santi Senesio e Teopompo	Medolla (MO)	2012
Chiesa di San Luca Evangelista	Medolla (MO)	2012
Chiesa dell'Immacolata Concezione	Crevalcore (BO)	2012

According to the macro-element approach, the typical portions whose behavior can be considered homogeneous under seismic actions have been identified. The recognition phase relied on the onsite application of the Italian survey form for churches, which includes 28 possible mechanisms [20] related to either out-of-plane or in-plane damage patterns, as well as to specific issues involving the main architectural components of the building (façade, triumphal arch, dome, transepts and naves, vaults, etc.) (Figure 1).

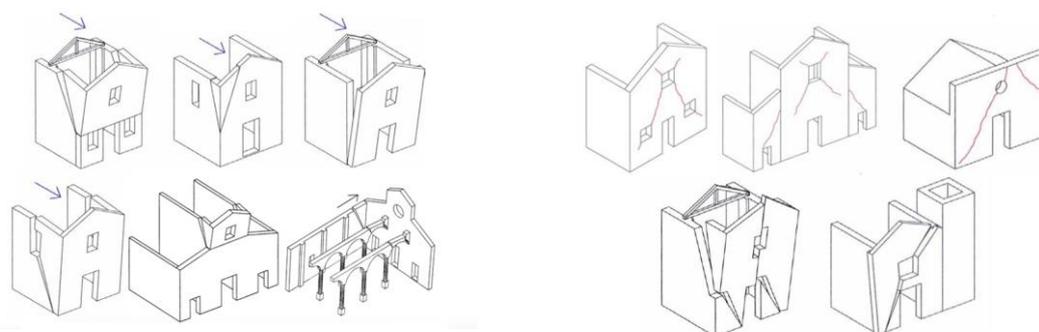


Figure 1. Example of out-of-plane (left) and in-plane (right) collapse mechanism of church façade [20].

Levels of damage are compared on a 1-to-5 scale, according to the European Macro Seismic Scale grading [21].

For the artistic assets, i.e., frescoes/mural paintings, stuccoes, and mosaics, the main aspects affecting damage were identified according to the Italian CNR-ICR recommendations [22]. As for vulnerability, no references are available as the study was carried out based on the comprehensive evaluation process provided by the reference survey forms of DataBAES [18]. They refer to both construction (composition, realization technique, etc.) and installation (application, position, intermediate support, etc.), as well as intrinsic variables (possible original defects).

2.2. Method: The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP), introduced by Saaty in the 1980s [12], is a general theory of measurement to obtain ratio scales from pairwise comparisons [23]. It is widely known in literature as a well-established multi-criteria approach and is applied by both academicians and practitioners in different context to systematize a wide range of decision problems. It proved to be useful when there is little quantitative information on the effects of the actions to be evaluated [24–28].

It grounds on the two basic principles that experience and people knowledge are as valuable as data in order to make a decision [12,25,29] and that measurements can be taken from actual measurement or from a fundamental scale, which reflects the relative strengths/importance of preferences. In this respect, the AHP allows for the measurement of tangible and/or intangible criteria and factors and allows for evaluating quantitative and qualitative criteria and alternatives on the same preference scale.

The AHP is based on the assumption that the decision-maker is always able to express a preference and judge the relative importance of (or preference for) the evaluation parameters [30–32]. In other words, it orders a finite number of actions A_i [12,33,34], by evaluating them with respect to a finite number k of attributes a_j ($j = 1, \dots, k$), each of which is assigned a judgment score qualifying its performance.

The individuals' ability to acquire and use information is used in the AHP process to determine relative magnitudes and importance through pairwise comparisons, which allows for constructing ratio scales on tangible and intangible factors and dimensions [35]. The AHP deconstructs the initial problem into several levels, constructing a hierarchy, which is an ordered set with unidirectional hierarchical relationships between different levels. The main goal of the decision problem represents the top of the hierarchy, whereas criteria and sub-criteria that contribute to the goal are positioned at lower levels. The bottom level is constituted by alternatives/actions to be evaluated. Then, a series of partial sub-decision problems are defined by structuring the problem through successive decomposition stages. These problems are smaller, less complex, and are easier to solve, since formulating a preference judgment is simpler when dealing with a limited number of decision criteria and expressing the individuals' opinions on two elements rather on all elements simultaneously. Consequently, relations within the hierarchical structure and elements relative importance are determined through pairwise comparisons. In detail, pairwise comparisons of the elements at each hierarchical level are conducted with respect to their relative importance towards their control criterion [35]. Expressed in semantic judgments are then converted into numerical values, according to Saaty's fundamental scale [12]. Saaty's scale is a scale of integers from 1 to 9 (Table 2), which has proven to be insensitive to small changes in numerical judgments [36,37].

Table 2. Saaty's fundamental scale (source Saaty, 1990).

Importance	Definition
1	Equal importance
3	Moderate dominance
5	Strong dominance
7	Demonstrated dominance
9	Extreme dominance
2,4,6,8	Intermediate values

Pairwise comparisons result in square matrices of preferences, where the dominance coefficient a_{ij} represents the relative importance of the component on row i over the component on column j . In detail, a_{ij} represents the relative importance of a certain criterion, sub-criterion or action A_i in comparison to another criterion, sub-criterion, or action A_j (Figure 2): the score of 1 represents equal importance of the two components, and 9 represents extreme importance of component i over component j [12,25]. Pairwise comparison matrices are square $n \times n$ positive reciprocal matrices of preferences, where the elements on the main diagonal are equal to 1, since the binary preference relation is reflexive, and the elements in the lower triangular sub-matrix are the reciprocals of the elements in the upper triangular sub-matrix ($a_{ji} = 1/a_{ij}$).

$$A = a_{ij} = \begin{matrix} & \begin{matrix} A_1 & A_2 & \dots & A_m \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \dots \\ A_m \end{matrix} & \begin{vmatrix} 1 & a_{12} & \dots & a_{1m} \\ 1/a_{12} & 1 & \dots & a_{2m} \\ \dots & \dots & \dots & \dots \\ 1/a_{1m} & 1/a_{2m} & \dots & 1 \end{vmatrix} \end{matrix}$$

Figure 2. Comparison matrix-

To solve each sub-decision problem, priorities (i.e., weights w_1, w_2, \dots, w_n), which reflect recorded judgements in a pairwise comparison matrix, are determined for consistent or near consistent matrices, where the relations between weights (w_i, w_j) and judgements (a_{ij}) are given by:

$$w_i/w_j = a_{ij} \text{ (for } i, j = 1, 2, \dots, n) \tag{1}$$

If the matrix A would be perfectly consistent, then $\lambda_{\max} = n$, where λ_{\max} is the maximum eigenvalue à la Perron-Froebenius of the pairwise comparison matrix [12], which represents the priority vector of a consistent $n \times n$ matrix (A) and is computed as the unique solution of $Aw = \lambda_{\max}w$. According to Saaty [38], the priority vector of a near consistent matrix, derived by small and continuous perturbation of an underlying consistent matrix A , can be obtained as a perturbation of the corresponding principal eigenvector of A [38]. It is nonetheless necessary to test the consistency of comparison matrices by calculating the so-called consistency index CI [39]. As small changes in a_{ij} generates small changes in λ_{\max} , the deviation of λ_{\max} from n (which coincides with the rank of matrix A) measures consistency. Therefore, the consistency index, which represents the “closeness to consistency” can be calculated as follows [12]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

In addition, Saaty recommends to determine the consistency ratio CR :

$$CR = \frac{CI}{RI} \tag{3}$$

where RI is a random consistency index which depends on the rank of matrix A [12,40].

CR is considered as an acceptable consistency ratio when it is less than 0.10 [12,41], whereas whenever $CR > 0.1$, a revision of pairwise comparison is recommended.

Absolute measurement is the comparison of some value on a scale with the unit value of the scale. Theories based on absolute require units of measurement to tradeoff weights for criteria or attributes. According to Saaty [35], measurements of phenomena on absolute scale serve as surrogates, indicators, or stimuli to the mind educated about the significance of magnitude of the number in terms of the goals and understanding of an individual. In a group, its members have to agree on how to interpret measurements to lend credence to objective acceptance. In the AHP absolute method an alternative is compared against an ideal property, i.e., a ‘memory’ of that specific property [42]. AHP absolute

models are implemented to rank each independent alternative at a time in terms of rating intensities for each criterion/sub-criterion. In an absolute model, the hierarchy is structured as usual into criteria and sub-criteria, which are further decomposed to a final level hierarchical level, which accounts for intensities through ratings [43,44]. In other words, according to [45], rating categories were established for each criterion and categories were prioritized by pairwise comparisons in terms of their preference, and then alternatives were evaluated by identifying an appropriate rating on each criterion.

It is worth noting that the typology (e.g., qualitative vs quantitative) and number of ratings may vary according to different criteria/sub-criteria. Each criterion is evaluated by an “intensity”. This intensity is identified by a numerical range of variation, which completes the bottom level or the hierarchy, and allows for numbering each alternative with respect to the criterion [46]. To define the relative weights for each criterion, according to the eigenvalue approach, the absolute measurement AHP requires a pairwise comparison procedure between indicator categories (i.e., high, low, etc.) and ideal preference synthesis: alternatives are compared to standard levels and are measured in an absolute scale, thus preserving rankings from rank-reversal issues and reducing the limitation on the number of alternatives to be compared [47–50].

3. Model

Firstly, to structure the decision problem, an extensive literature review was conducted. Secondly, to identify key issues and construct the hierarchy, a group of nine experts representing three main perspectives (knowledge, government, and business) were selected [51,52]. Group decision making benefits de facto from the plurality of its members [53] to capture as much diversity of thinking as possible and to reach consensus on the final decision in a systematic and credible way [54].

Focus groups were organized, and a Delphi survey-based process was implemented to create consensus on criteria and sub-criteria, obtain experts’ judgments, and validate the final hierarchy through dynamic discussion [25,31,51,54]. In order to ensure the best representability, the group of nine experts consisted of six academicians and professionals with proven expertise in cultural heritage conservation and preservation, seismic risk assessment, structural dynamics, art history, history of architecture, a representative from construction companies specialized in restoration and retrofit of cultural heritage assets, a representative of Superintendence, and a representative from the Italian Civil Protection Department.

The panel of experts identified seven hierarchical levels from the goal at the top of the hierarchy (i.e., ranking alternatives according to priorities of intervention) to ratings at the bottom of the tree-like structure, and identified three main criteria which represent a first-level decomposition of the building structure into foundations, above-ground structure, and horizontal components. These criteria were then decomposed into nine sub-criteria and 26 sub-sub-criteria (Table 3). The graphical representation of the hierarchy is included in the Supplementary Materials of this paper.

In order to determine the weights of criteria, sub-criteria and sub-sub-criteria once the panel reached consensus on the hierarchy and validated it, the model was firstly implemented on the *Super Decision* Software, and each expert was asked to compile the entire set of pairwise-comparison matrices in a face-to-face interview. Secondly, the CI for each matrix was calculated and proved to be within the acceptability limit (i.e., $CI < 0.1$). Subsequently, each expert’s judgements were combined and weights were aggregated by calculating judgements geometrical mean (Table 4). According to group decision making theory, this procedure allows for making a synthesis of individual judgements expressed with respect a single pairwise comparison as the representative judgment for the entire group [25,55,56].

Table 3. Description of criteria, sub-criteria, and sub-sub-criteria.

Criteria	Description
D1–Foundation	Structure composing foundations
D2–Above-ground structure	Structural elements composing the surface structure
D3–Horizontal components	Floors and roof
Sub-criterion D2	Description
D2.1–triumphal arch	Wall archway opposite to façade
D2.2–apse	Semicircular or polygonal recess, arched or with a domed roof
D2.3–nave	Main body of a church between façade and triumphal arch enclosed either between aisles or lateral walls
D2.4–bell-tower	Tower with a belfry containing bells, included, adjacent or detached from the church
D2.5–lateral chapel	Small room adjacent to the main walls of the church
D2.6–façade	External main face of the church
D2.7–transept	Transverse portion lying across the main body of the church
Sub-criterion D2.1	Description
D2.1.1–mural painting	Decorative painting applied to immovable substrate
D2.1.2–mosaic	Patterned surface composed of tesserae
D2.1.3–none	Absence of decoration on substrate
D2.1.4–stucco	Decorative plasterwork
Sub-criterion D2.2	Description
D2.2.1–apse overturning	Out-of-plane rotation
D2.2.2–shear mechanism	Shear deformation/cracking of masonry walls
D2.2.3–presbytery/vaults of apse	Shear deformation/cracking of masonry vaults
Sub-criterion D2.3	Description
D2.3.1–transverse response	Out-of-plane displacement of one or more lateral walls
D2.3.2–shear mechanism	Shear deformation/cracking of masonry walls
D2.3.3–response of colonnade	Shear deformation/cracking due to in-plane actions in colonnade
D2.3.4–vaults of nave	Shear deformation/cracking of vaults of central nave
D2.3.5–vaults of side aisle	Shear deformation/cracking of vaults of side aisles
Sub-criterion D2.4	Description
D2.4.1–belfry	In-plane deformation of arches or pier ends
D2.4.2–bell tower	Rotation of tower or in-plane deformation of walls
D2.4.3–projections	Out-of-plane rotation or displacement of projections
Sub-criterion D2.5	Description
D2.5.1–overturning	Out-of plane rotation of lateral chapels
D2.5.2–shear mechanisms	In-plane shear deformation/cracking
D2.5.3–vaults of chapels	Shear deformation/cracking on vaults of chapels
D2.5.4–irregularities on plan and elevation	Deformations due to interaction with adjacent structures
Sub-criterion D2.6	Description
D2.6.1–overturning	Out-of-plane overturning of façade
D2.6.2–in-plane mechanisms	In-plane shear deformation or tensile cracking of façade
D2.6.3–mechanisms at top part	Out-of-plane flexural displacement at top
D2.6.4–prothyrum or narthex	Out-of-plane flexural displacement of prothyrum or narthex
Sub-criterion D2.7	Description
D2.7.1–overturning of end wall	Out-of-plane overturning of end walls of transept
D2.7.2–shear mechanisms	Shear deformation/cracking
D2.7.3–vaults of transept	Shear deformation/cracking of vaults
Sub-criterio D2.i,j where $2 < i < 7$ e $1 < j < 5$	Description
D2.i,j.1–mural painting	Decorative painting applied to immovable substrate
D2.i,j.2–mosaic	Patterned surface composed of tesserae
D2.i,j.3–none	Absence of decoration on substrate
D2.i,j.4–stucco	Decorative plasterwork
Sub-criterion D3	Description
D3.1–roofing	Roof structure of the church
D3.2–matroneum (floors)	Balcony or porch for women; horizontal floor
Sub-criterion D3.1	Description
D3.1.1–dome	Roofing cap covering squared, circular or polygonal rooms di vani a pianta quadrata, circolare o poligonale
D2.1.2–roof of building	Main roof structure made of timber trusses covered by secondary wooden framework and roof tiles
Sub-criterion D3.1.1	Description
D3.1.1.1–lantern	Shear deformation/cracking of cap or torsional rupture of base of pillars
D3.1.1.2–lantern tower/drum	Shear deformation/cracking of dome with extension to drum
Sub-criterio D3.1.i,j where $1 < i < 2$ e $1 < j < 2$	Description
D2.i,j.1–mural painting	Decorative painting applied to immovable substrate
D2.i,j.2–mosaic	Patterned surface composed of tesserae
D2.i,j.3–none	Absence of decoration on substrate
D2.i,j.4–stucco	Decorative plasterwork

Table 4. Aggregation of experts' judgements on criteria, sub-criteria and sub-sub-criteria, and final priority vector.

Goal	Priority Vector
foundations	0.3196
above-ground structure	0.5584
horizontal components	0.1220
CI	0.01759
Criterion D2	Priority vector
triumphal arch	0.1375
apse	0.0609
nave	0.2507
bell tower	0.0222
lateral chapel	0.0270
façade	0.4170
transept	0.0845
CI	0.07515
Sub-criterion D2.1	Priority vector
mural painting	0.4673
mosaic	0.2772
none	0.0954
stucco	0.1601
CI	0.01160
Sub-criterion D2.2	Priority vector
apse overturning	0.6483
shear mechanisms	0.2297
presbytery/vaults of apse	0.1220
CI	0.00355
Sub-criterion D2.3	Priority vector
transverse response	0.5360
shear mechanisms	0.0533
response of colonnade	0.2246
vaults of nave	0.1166
vaults of side aisle	0.0696
CI	0.05971
Sub-criterion D2.4	Priority vector
belfry	0.2785
bell tower	0.6630
projections	0.0585
CI	0.05156
Sub-criterion D2.5	Priority vector
overturning	0.5781
shear mechanisms	0.2282
vaults of chapels	0.1336
irregularities on plan and elevation	0.0601
CI	0.02524
Sub-criterion D2.6	Priority vector
overturning of façade	0.5610
in-plane mechanisms	0.0963
mechanisms at top part	0.2960
prothyrum or narthex	0.0467

Table 4. Cont.

Goal	Priority Vector
CI	0.07311
Sub-criterion D2.7	Priority vector
overturning of end wall	0.6483
Shear mechanisms	0.2297
vaults of transept	0.1220
CI	0.00355
Criterion D3	Priority vector
roofing	0.8333
matroneum (floors)	0.1667
CI	0.0001
Sub-criterion D3.1	Priority vector
dome	0.750
roof of building	0.250
CI	0.0002
Sub-sub-criterion D3.1.1	Priority vector
lantern	0.125
Lantern tower/drum	0.875
CI	0.0001
Sub-sub-criterion D2.i.j (2<i<7 and 1<j<5); Sub-sub-criterion D3.1.i.j (1<i<2 and 1<j<2)	Priority vector
mural painting	0.4673
mosaic	0.2772
none	0.0954
stucco	0.1601
CI	0.0116

Finally, the panel of experts subdivided the bottom level of the hierarchy into a level for intensities and listed ratings under each sub-criterion or sub-sub-criterion. Ratings were identified according to the Italian survey form for churches [20] and correspond to six damage levels: null, low, moderate, high, very high, and collapse. The experts subsequently pairwise compared the six levels of intensities (i.e., damage levels) above mentioned in terms of priority with respect to the parent node and set equal ratings for all of the sub-criteria (Table 5).

Table 5. Ratings priority.

	Priority Vector
collapse	0.4830
very high	0.1921
high	0.1874
moderate	0.0646
low	0.0427
null	0.0302

4. Results and Discussion

The model was implemented to rank multi-criteria prioritization of protection and restoration interventions on a set of 15 Italian churches (i.e., alternatives), listed in the DataBAES and damaged by earthquakes, which occurred in Italy in the last decades. Prior to this, it was compiled in an evaluation

matrix to identify for each alternative its characteristics and assess its damages to both structural elements and pieces of art. Subsequently, each alternative was rated by assigning it intensity ratings, which characterize the alternative with respect to criteria (sub-criteria, sub-sub-criteria).

Table 6 summarizes the global priority vector and the ranking of alternatives with respect to the goal.

Table 6. Global priority vector and ranking of alternatives.

Church	Priority (Normal Values)	Ranking
Chiesa di Sant' Antonio	0.233600	1
Chiesa di San Marco	0.130948	2
Cappella degli Scrovegni	0.121087	3
Chiesa Madre	0.100648	4
Chiesa di San Silvestro	0.073573	5
Chiesa di Santa Maria delle Grazie	0.072700	6
Chiesa del Santo Rosario	0.060274	7
Chiesa dell'Annunziata	0.037264	8
Chiesa di S. Egidio	0.034368	9
Chiesa dei Santi Senesio e Teopompo	0.034363	10
Complesso di Santa Maria ai Monti	0.019805	11
Chiesa di San Luca Evangelista	0.008256	12
Complesso della Madonna del Carmine	0.001544	13
Chiesa di San Michele Arcangelo	0.001054	14
Chiesa dell'Immacolata Concezione	0.000713	15

According to our findings, the church which requires the most urgent intervention is “Chiesa di San Antonio”, located in San Potito Ultra in Avellino (South of Italy), which was damaged by the earthquake that occurred in Irpinia in 1980. Its top position in the ranking is due to both the collapse of the dome, which in turn caused the loss of a fresco, and the activation of mechanisms involving the triumphal arches. This mechanism is probably related to the damage of the dome. However, although its priority is low, it must be taken into consideration to prevent from future worsening caused by a new seismic event. The “Chiesa di San Marco in l'Aquila” (central Italy), which was damaged by the earthquake that occurred in Abruzzo Region in 2009, is ranked as second. Several out-of-plane damage were identified, which involved stuccoes, although the limited extension did not affect the final evaluation for this church. The “Cappella degli Scrovegni” in Padova included 20 cases of damage to frescoes and is ranked as third, although at current no signs of mechanism activation can be observed. The priority, in this case, is due to the valuable cycle of Giotto's frescoes, although no significant risk for the structure is detected.

At the bottom of the hierarchy there are the “Chiesa di San Michele Arcangelo” in Saviano in Naples (South of Italy), and the “Chiesa dell'Immacolata Concezione” in Bologna (Central Italy) respectively. They both have limited damage for their stuccoes. The difference in ranking between the two churches is due to the damage mechanism, respectively referred to the more brittle mechanism of the vault of the transept than the in-plane behavior of the apse walls.

5. Conclusions

The occurrence of natural disasters such as earthquakes represent a worldwide challenge in the conservation of cultural heritage (CH), which suffer from damage due to high vulnerability conditions. Therefore, the protection of CH from seismic hazard is of paramount importance. As the protection of CH involves high investment costs, which usually exceeds available financial resources, it is necessary to prioritize interventions and rank CH assets according to their vulnerability. In order to create a one-dimensional index for representing the overall assessment of alternatives, an AHP absolute model was developed. Based on literature review and expert judgements, six hierarchical levels (from goal to ratings), criteria, sub-criteria and ratings were identified, and local priorities and

global priorities were determined according to the eigenvalue approach to pairwise comparisons. The model was then validated by ranking 15 Italian churches damaged by earthquakes occurred over the last decades. Our results mirror the results from DataBAES web archive, which correlates vulnerability and damage of artistic assets to damage and vulnerability of their related structural components. Once the model had been validated, it can be implemented to rank a wide set of CH churches, independently from the need to pairwise compare alternatives one another. The ranking de facto depends on data/information collected during on site visual inspection and can be extended to include new alternatives under investigation to the original set without requiring to re-set local and global priorities, thanks to absolute measurements here adopted. This model can provide a valid and robust decision support tool to Governments and Public Administrations in the design of effective conservation strategies, which require the stabilization of severely damaged buildings and the preventive improvement of constructions structural response to seismic actions and the management of the seismic post-emergency phase.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/4/1608/s1>.

Author Contributions: Conceptualization C.D. and M.R.V.; methodology C.D.; software C.D.; validation, C.D. and M.R.V.; formal analysis, C.D. and M.R.V.; investigation C.D. and M.R.V.; data curation, C.D. and M.R.V.; writing C.D. and M.R.V. All authors have read and agree to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful to Anita Pezzolo for administering questionnaire to the panel of experts and data survey.

Conflicts of Interest: The authors declare no conflict of interest.

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