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SCREENING PROCEDURE FOR THE RISK ANALYSIS OF CULTURAL HERITAGE ASSETS

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Abstract

A simplified risk assessment framework specifically developed for built immovable cultural heritage assets is proposed. The framework addresses all the components in a risk analysis and can be used as a screening procedure for the preliminary assessment of a large number of assets with limited resources. Furthermore, the framework can also be used to identify cultural heritage assets that require a more refined and resource demanding risk evaluation. The proposed risk analysis framework falls into the category of qualitative methods and is based on an existing approach developed for the vulnerability assessment of critical infrastructures. The qualitative risk analysis of the proposed methodology is based on a series of structured questionnaires that address the main components of a risk analysis: the likelihood of the hazard, the consequences of the hazard, the vulnerability of the asset to the hazard, the loss of value of the asset and the capacity to recover from the event. To illustrate the applicability of the proposed methodology, an application example is also presented for the case of seismic risk.

Keywords: risk assessment, vulnerability, hazard, built immovable cultural heritage, cultural heritage value

1. Introduction

Over the years, several international initiatives have been promoted to address the issues of disaster risk reduction and disaster risk management in order to establish new approaches to reduce the impact of disasters in society. In 2005, the adoption of the Hyogo Framework for Action (HFA) 2005-2015 was an important step towards these objectives. The HFA was the first internationally accepted framework where international agencies and national governments have set targets and commitments for disaster risk reduction (DRR) which were defined through five priorities for action. Of those five priorities, Priority Action 2 specifically addresses risk assessment and monitoring. Therefore, the HFA clearly acknowledges that the sustainable implementation of disaster mitigation actions can only be achieved when based on adequate knowledge regarding the hazards threatening relevant assets and their vulnerability to those hazards. Even though the HFA has ended in 2015, efforts towards DRR continue since the HFA has now been replaced by the Sendai Framework for Disaster Risk Reduction 2015-2030. This new framework is expected to build on the achievements of the HFA to establish a set of improvements. Among other aspects, the importance of cultural heritage and its irreplaceable value for society have been explicitly recognized, thus emphasising the need to assess the impact that potential hazards such as earthquakes may have on cultural heritage.

Despite these concerns, irreplaceable losses of cultural heritage continue to occur throughout the world as a result of earthquakes. Even though numerous cultural heritage assets require the implementation of risk mitigation measures, the development of such measures needs to be based on adequate knowledge about the risk these assets are facing. However, for most countries, carrying out an earthquake risk analysis for a large number of cultural heritage assets requires efforts and budgets that are frequently unavailable. Therefore, assessing the risks for a large number of assets with limited resources is only feasible when based on simple methodologies.

To address this need, a simplified methodology is proposed herein which can be used as a screening procedure for the preliminary earthquake risk analysis of cultural heritage assets. The proposed methodology addresses all the components in a risk analysis and can be used as a screening procedure for the preliminary assessment and identification of specific cultural heritage assets that require a more refined and resource demanding risk evaluation. The qualitative risk analysis of the proposed methodology is based on a series of structured questionnaires that address the main components of a risk analysis. To illustrate the proposed framework, its application is presented for the seismic risk analysis of a church damaged by the 2009 L'Aquila earthquake. The results are compared with the damages suffered by the church due to the referred earthquake.

2. Proposed framework for the simplified risk analysis of cultural heritage assets

2.1 General overview of the framework

The simplified methodology proposed herein can developed for the preliminary risk analysis and prioritizing of built immovable cultural heritage units. A cultural heritage unit is considered to be a single property or a component that is part of a property for which a risk analysis is required (e.g. a church is a unit but the bell tower of a church may also be considered to be a unit if necessary). The proposed risk analysis framework falls into the category of qualitative methods and is based on an existing approach developed for the vulnerability assessment of critical infrastructures [1]. The proposed methodology is based on a series of structured questionnaires that address the main components of a risk analysis: the likelihood of the hazard, the consequences of the hazard, the vulnerability of the asset to the hazard, and the capacity to recover from the event. Figures 1 and 2 illustrate the full scope of the questionnaires and outcomes that can be obtained with the proposed framework. Figure 1 presents the part of the method that establishes the vulnerability of the cultural heritage unit and Fig. 2 presents the part where the vulnerability is combined with the hazard to determine the risk level. As can be seen, the process of Fig. 1 establishes five classes of increasing vulnerability (V_I to V_V) which are defined by answering questions that address the different components contributing to the vulnerability. It is noted that the process also accounts for the case where a certain cultural heritage unit may have an irrelevant level of risk (R_0) if its level of exposure to the hazard under consideration is not relevant. The process of Fig. 2 can be seen to establish five classes of increasing risk (R_I to R_V) based on the vulnerability classes defined by the process of Fig. 1, V_I to V_V, and on the expected likelihood of the hazard.

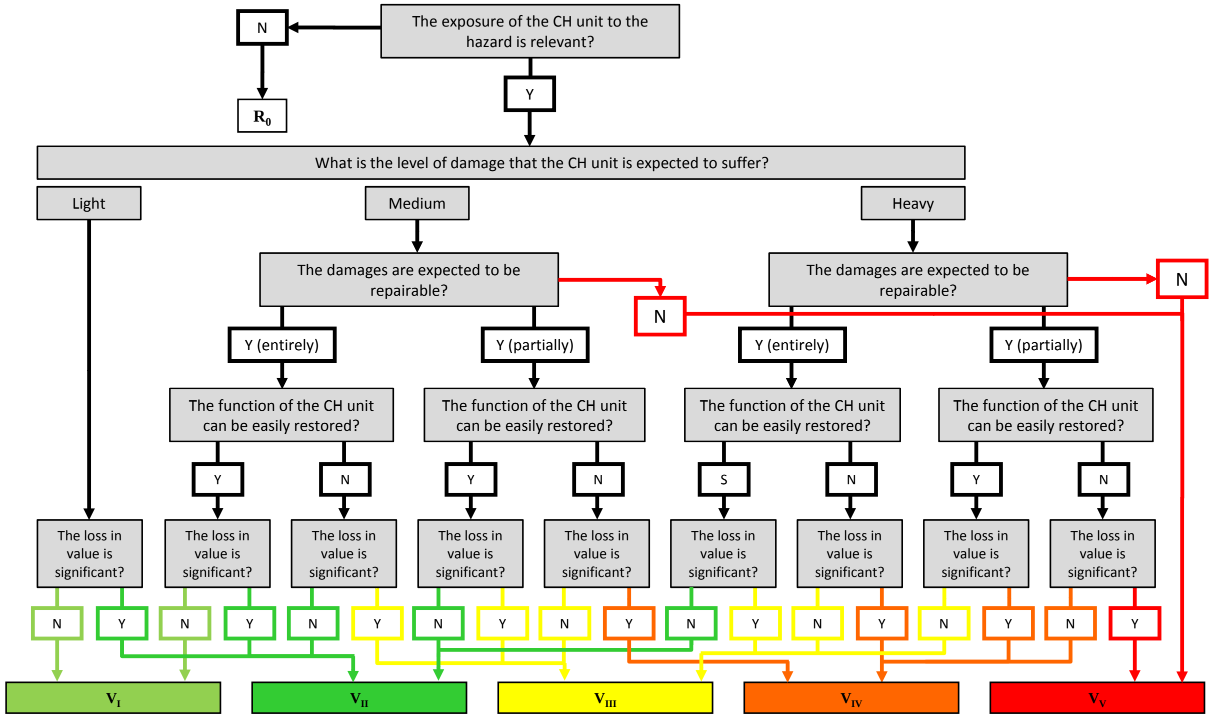


Fig. 1. Proposed risk analysis methodology: assessing the vulnerability of the cultural heritage (CH) unit.

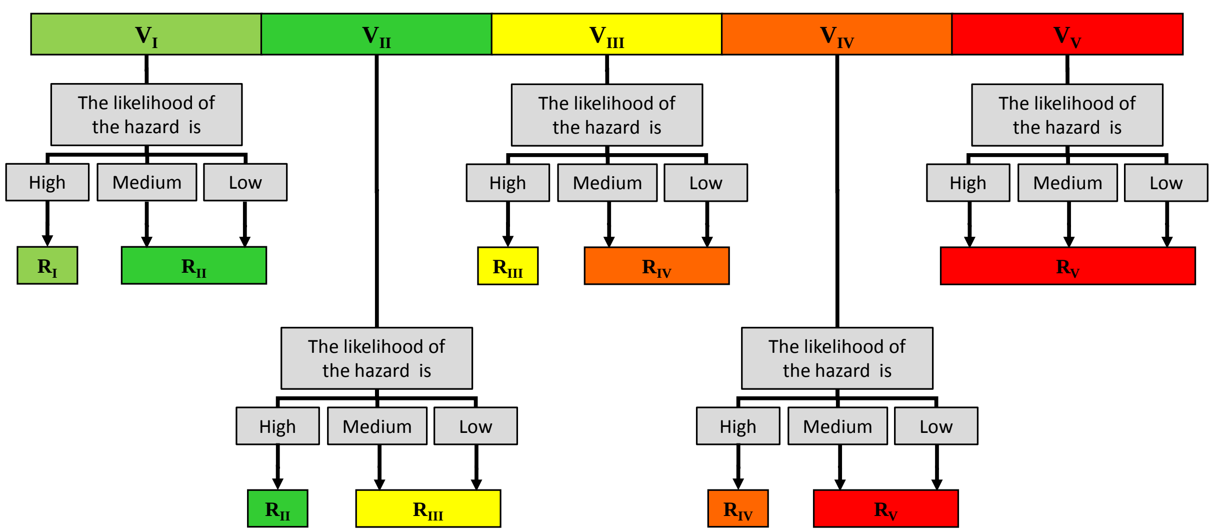


Fig. 2. Proposed risk analysis methodology: assessing the risk of the cultural heritage (CH) unit.

The proposed framework considers three categories of expected hazard likelihood which are termed High, Medium and Low. These hazard categories depend on the type of hazard but must reflect the fact that an event with a High likelihood is expected to have a lower hazard intensity while a Low likelihood event is expected to have a higher hazard intensity. For example, for the case of earthquakes, a High likelihood event is expected to have a lower average return period and also a lower magnitude, while for a Low likelihood event it is the opposite. From Fig. 2 it can be seen that, for a given vulnerability level, when the expected likelihood of the hazard is High or Medium, the subsequent risk level is the same. This conservative approach was considered in order to reduce the number of risk categories that result from the proposed framework. Furthermore, it can also be seen that when the vulnerability level is V_V, the subsequent risk level is always R_V, irrespective of the expected likelihood of the hazard. In this case, the framework assumes that if a cultural heritage unit exhibits the highest level of vulnerability, the severity of this condition implies the need to also consider the highest level of risk. Based on the characteristics of the proposed framework, this methodology is believed to be applicable to any type of cultural heritage unit threatened by any type of hazard and can be used to carry out a structured qualitative risk analysis. The application of the procedure starts by the definition of the hazard scenario for which the risk analysis of a certain cultural heritage unit is required. After defining this scenario, the analyst will then go through the questionnaire of Fig. 1 to establish the vulnerability level. The questionnaire of Fig. 2 is then used to combine the vulnerability level with the likelihood of the hazard scenario initially defined and obtain the risk level. To provide further guidance for the application of the framework, additional aspects that need to be considered when analysing the vulnerability classification are addressed in the following.

2.2 Characterization of the vulnerability analysis components

After defining the hazard scenario and establishing that the exposure of the cultural heritage unit to that scenario is relevant, the next step of the vulnerability assessment involves classifying the expected level of damage of the cultural heritage unit for that scenario. This expected level of damage needs to be defined according to one of three possible classes: *Light*, *Medium* or *Heavy*. The following descriptions can be used as a reference:

- *Light* damage corresponds to the case where the cultural heritage unit only exhibits non structural damage (i.e. damage that will not affect the resisting system and the overall stability of the cultural heritage unit);
- *Medium* damage corresponds to the case where the cultural heritage unit exhibits more severe non structural damage and also suffers moderate structural damage (i.e. damage that will affect the resisting system of the cultural heritage unit without compromising its overall stability);
- *Heavy* damage corresponds to the case where the cultural heritage unit exhibits severe structural damage that can make it unstable (i.e. the overall stability of the cultural heritage unit is compromised) or that can cause the partial or total collapse of the cultural heritage unit.

Given the qualitative nature of the proposed framework, the expected level of damage of a given cultural heritage unit can be estimated using a simplified procedure such as expert elicitation or an indicator-based approach. For the cases of earthquake, flood, fire, hydro-meteorological, landslide and storm hazards, the procedures and data found in [2-7] can be used to define simplified indicator-based approaches suitable to estimate the expected level of damage. For the particular case of earthquake hazard, the authors have developed a set of simplified indicator- and mechanics-based procedures for specific types of cultural heritage units [8]. Additional details of these approaches are addressed in the following Sections.

In case there are heritage assets attached to the main cultural heritage unit (e.g. tiles, mural paintings, etc), the vulnerability analysis of the cultural heritage unit should also account for these elements. This influence is, however, only accounted for in the subsequent stages of the vulnerability analysis, even though the damages to these attached heritage assets and those of the cultural heritage unit are correlated. The proposed framework assumes that if *Light* damage is expected in the cultural heritage unit, the damages to the attached cultural assets will be either negligible or fully restorable. As such, only the potential loss of value is analysed in this case (Fig. 1). If the expected damage is *Medium* or *Heavy*, the classification of the following stages of the vulnerability analysis will need to consider the damage and loss in value to both the cultural heritage unit and the attached heritage assets.

For the cases where the expected level of damage is expected to be *Medium* or *Heavy*, the next component of the framework analyses if those damages are repairable (fully or partially) to determine if it will be possible to reuse the cultural heritage unit as before the occurrence of the damaging event. Damages are considered to be repairable if it is physically and technically possible to restore the physical and material integrity of the cultural heritage unit. In this context, the following repair possibilities should be examined:

- Restoring the materials to their initial conditions without compromising the authenticity of a cultural heritage unit (which may be connected to its value);
- Stabilizing the damaged elements without masking or hiding the results of the repair, strengthening, reconstruction or consolidation process carried out in the cultural heritage unit.

Since the expected level of damage was defined in terms of structural and non structural damage, the reparability analysis must be carried out separately for these two types of damages. Furthermore, if there are heritage assets attached to the main cultural heritage unit, this analysis must also account for these elements. As before, expert elicitation and judgement based on the characteristics of the cultural heritage unit under analysis is expected to be instrumental to assess the expected damage reparability.

After classifying the possibility of repairing the expected damage, the framework then analyses how easy will it be to restore the function of the cultural heritage unit back to its pre-damaging event state (even if only partially). According to the proposed framework, this stage of the analysis is expected to reflect and characterize the resilience of the cultural heritage unit. To perform this classification, the time, human and financial resources necessary to repair and/or stabilize the damages need to be analysed. In addition, resources that may be required to restore and/or develop the human and technical means necessary for the activities associated to the function of the cultural heritage unit must also be accounted for. In this context, it is noted that the ability to restore the pre-damaging event function may depend on factors other than those directly related to the cultural heritage unit. For example, factors related to heritage assets that may be attached to the main cultural heritage unit (e.g. tiles, mural paintings, etc) or movable heritage assets (e.g. museum collections) that may be inside the main cultural heritage unit should be considered in this stage if they are found to be relevant to its function. As for the previous stages, expert elicitation and judgement will be instrumental to classify this stage. As a suggestion, if the availability of human and financial resources is not a restriction, the function of the cultural heritage unit can be considered to be easily restored if it occurs up to 6 months after the end of the post-event emergency response operations.

Finally, the last stage of the vulnerability assessment analyses the significance of the expected loss in value of the cultural heritage unit. Given the simplified nature of the proposed vulnerability assessment process and the well-known difficulties in defining the multiple dimensions of cultural heritage value, the loss of value analysis must also be based on simple qualitative principles. In this analysis, it is suggested that the following five types of value, which are partially based on [9], should be considered to analyse the expected loss of value of a certain cultural heritage unit:

- *Evidential value*: it derives from the potential of the cultural heritage unit to yield evidence about past human activity (physical remains, written records, archaeological deposits, etc.).
- *Historical value*: it derives from the ways in which past people, events and aspects of life can be connected through the cultural heritage unit to the present (it can be divided into (a) illustrative value: the extent to which it illustrates something particular or distinctive; (b) associative value: the extent to which it is associated with a notable family, person, event or movement).
- *Aesthetic value*: it derives from the ways in which people draw sensory and intellectual stimulation from the cultural heritage unit (either as a result of conscious design or the seemingly fortuitous outcome of the way in which the cultural heritage unit has evolved and has been used over time).
- *Communal value*: it derives from the meanings of the cultural heritage unit for the people who relate to it, or for whom it figures in their collective experience or memory (these can include (a) commemorative and symbolic values: the meanings of a place for those who draw part of their identity from it, or have emotional links to it; (b) social value: places that people perceive as a source of identity, distinctiveness, social interaction and coherence; and (c) spiritual value: emanate from the beliefs and teachings of an organised religion, or reflect past or present-day perceptions of the spirit of place).
- *Economic value*: it derives from the potential of the cultural heritage unit to produce financial dividends for society as a result of direct or indirect economic activities connected to the use and function of the cultural heritage unit.

The expected loss in value can be connected to more than one class, depending on the type of cultural heritage unit under consideration. Therefore, the analysis of the expected loss in value should consider the relative importance of each of the five classes of value, which needs to be defined case by case. In general, the expected loss of value will depend on the expected level of damage as well as on the possibility of repairing such damage. In some cases, the expected loss of value will also need to consider how easy it is to restore the function of the cultural heritage unit since this factor may be particularly relevant for the loss of economic value. Furthermore, it is also noted that the uniqueness and rareness of a given cultural heritage unit should be reflected in the expected loss of value analysis and it may be associated with any of the referred classes of value. As for the previous stages, expert elicitation and judgement is expected to be instrumental to classify this stage. As for the previous stages, if there are heritage assets attached to the main cultural heritage unit, their contribution to the loss in value should also be accounted for. However, it is noted that this analysis does not include potential losses to movable heritage assets that may be inside the main cultural heritage unit. In relevant cases, a separate analysis of the expected loss of value to these heritage assets should be performed using a suitable methodology.

3. Detailing of the framework for earthquake risk analysis

As previously referred, the risk analysis framework was further developed for the particular case of earthquake hazard. Given that different types of constructions exhibit different behaviours under earthquakes, cultural heritage units need first to be assigned to architectural classes reflecting those differences. Based on these classes, analysis procedures can then be defined for each class which account for their specific behaviour under earthquakes. In the context of seismic analysis, a general classification of cultural heritage units has been defined in [10] that proposes six classes accounting for the construction morphology and the building technology. Since the detailing of the proposed framework for earthquake risk analysis was not developed for all types of constructions, a classification is proposed herein establishing only four architectural classes (CA1 to CA4) partially based on [10]. The architectural classes considered herein only involve masonry constructions and a different method was defined for each class to analyse the expected level of earthquake damage. The architectural classes that were considered are described in Table 1 and Figs. 3 to 6 present a few examples of cultural heritage units of each class.

Table 1 – Architectural classes of masonry constructions considered in the proposed framework.

Architectural class	Description
CA1	Single-storey or multi-storey masonry building
CA2	Hollow slender masonry construction
CA3	Solid slender masonry construction
CA4	Arched masonry construction

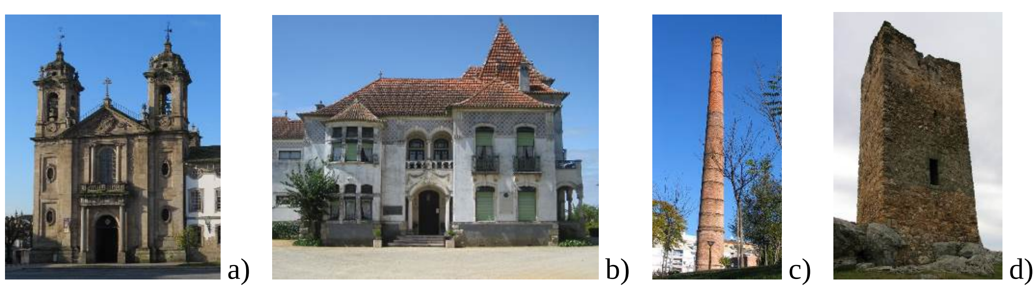


Figure 3 – Examples of constructions from the architectural classes CA1 a), b); and CA2 c), d).

Figure 4 – Examples of constructions from the architectural CA3 a), b); and CA4 c), d).

For each type of architectural class, simplified indicator- and mechanics-based procedures were developed to establish the expected level of damage under a given scenario of earthquake occurrence. These procedures are based on the classification of several parameters related, for example, to the geometry and shape of the cultural heritage unit, to its integration with the surrounding environment, to the type of structural system, to the quality of the materials, and to its state of conservation. For each architectural class, a specific data form and manual were developed to record all the necessary parameters and determine the expected level of damage. The detailed description and definition of the data forms and manuals developed for the four architectural classes are presented in [8] but are unable to be reproduced herein for the sake of brevity. However, it is referred that the procedure developed for cultural heritage units of class CA1 is based on the classification and weighted average of 14 parameters related to the type of structural system, the characteristics of the masonry, the lateral strength of the structure, geometric factors such as the maximum distance between walls and the height of the building, the type of foundations and soil conditions, the building position and interaction with respect to its surroundings, plan and vertical regularity factors, the type and arrangement of openings, the type of floor system, the type of roof system, the state of conservation of the structural system and the existence of non-structural falling hazards. The weighted average of these parameters leads to the quantification of a fragility index which is then correlated with the level of expected damage. The procedure developed for cultural heritage units of class CA2 is similar to that of class CA1. For class CA2, the procedure is based on the classification and weighted average of 12 parameters related to the type of structural system, the characteristics of the masonry, the lateral strength of the structure, the slenderness of the structure, the type of foundations and soil conditions, the construction position and interaction with respect to its surroundings, plan and vertical regularity factors, the type and arrangement of openings, the type of floor and roof systems, the state of conservation of the structural system and the existence of non-structural falling hazards. The procedures developed for cultural heritage units of classes CA3 and CA4 are different than those of classes CA1 and CA2 since they are mostly based on simple mechanics-based approaches. For class CA3, the expected level of damage is determined from the overturning stability of the construction and its sensitivity to develop a rocking mechanism. In this case, the procedure depends on the geometric and material properties of the construction, the type of foundations and soil conditions, the dynamic properties and the slenderness of the construction. For class CA4, the expected level of damage is determined by analysing the stability of single or multiple arch systems with respect to transversal failure mechanisms. The procedure depends on the geometric characteristics of the structure (i.e. single or multiple arch system, type of pier, type of abutment, dimensions), the out-of-plane strength of the spandrel wall, the out-of-plane global arch-piers strength and the soil conditions.

Since the data required for each form needs to be obtained from existing documentation and in situ surveys, the level of reliability of the data that is considered is also established in the form. This way, the level of expected damage that is determined is also assigned with an uncertainty measure to establish its reliability. Depending on this level of reliability, the result of the damage analysis may then be considered valid or not.

4. Application to the seismic risk analysis of the Church of Santa Maria ad Cryptas

To illustrate the applicability of the proposed framework, a case study corresponding to the seismic risk assessment of the Church of Santa Maria ad Cryptas, in Italy, is presented for an earthquake scenario compatible with the L'Aquila earthquake of 2009. For the purpose of determining the level of expected damage, the Church of Santa Maria ad Cryptas was considered to be a cultural heritage unit from the architectural class CA1. The procedure leading to the level of expected damage is described and comparisons are made with the damage sustained by the church during the 2009 L'Aquila earthquake.

4.1 Description of the Church of Santa Maria ad Cryptas

The church of Santa Maria ad Cryptas is located about 1 km away from the centre of Fossa, an old village 12 km East of L'Aquila (Italy). This church was built in the second half of the 13th century, probably on the remains of a previous 9th century temple, and is among the best examples of Gothic art in the Abruzzo region. The very simple church configuration (Fig. 5) has two buttresses on the left side to strengthen the church that stands on a sloped hillside on that side. The entrance of the church shows some Romanesque influences but it is one of the first Gothic examples in Abruzzo. The interior follows the Cistercian model with a single nave divided into three bays and a square apse located on the south-east side. In front of the presbytery, a ladder leads to the small crypt, which according to historians was originally an underground dedicated to the worship of the goddess Vesta. A wooden truss roof covers both the nave and the apse. The ceiling of the apse is a 12th century cross vault with stone ribs and brick infill panels. The simple architectural layout of the church and its external simplicity (Fig. 6) are in high contrast with the richness of the frescoes decorating the walls, arches and vaults (Fig. 6) [11]. As can be seen from Fig. 5, the church has an approximately rectangular plan with dimensions 12 × 22 m^2 and the height of the walls ranges between 7 m and 9 m. According to [12], the church walls are made of limestone blocks with lime and sand mortar. Two types of walls can be identified from the exterior: the façade made of a regular assembly of squared limestones laid in regular courses and the remaining walls made with irregular stone units poorly shaped, which have dimensions similar to those of the façade but are laid in irregular courses. According to a survey carried in 2007 [13], the church exhibited some damages prior to the earthquake. These damages involved the development of cracks in the façade and lateral walls, traces of lack of mortar/incipient splitting of the masonry, as well as capillary humidity coming from the ground that led to biological attacks in the bottom part of some of the walls.

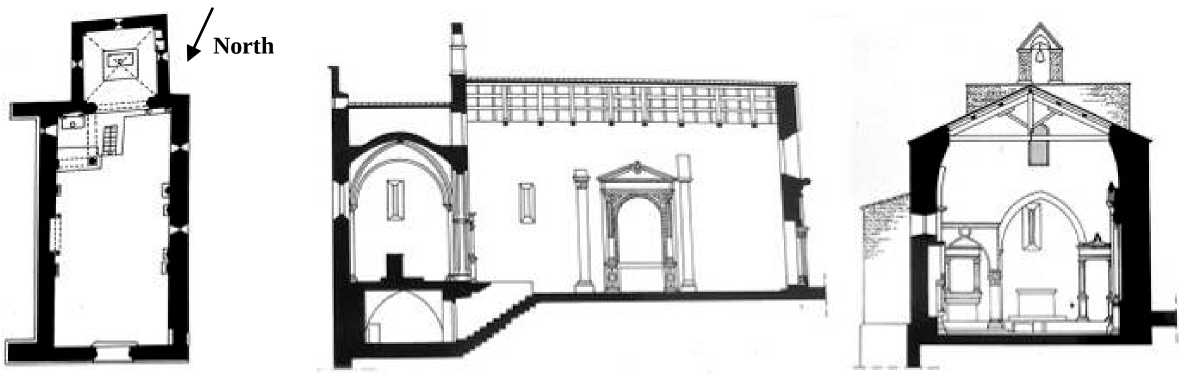


Figure 5 – Plan and cross section views of the Church of Santa Maria ad Cryptas.

Figure 6 – External view of the of the Church of Santa Maria ad Cryptas (left) and interior views of the frescos.

4.2 Determining the expected level of damage for constructions of architectural class CA1

According to the procedure detailed in [8], the expected level of damage of constructions belonging to architectural class CA1 is determined by first quantifying a fragility index *IFS* whose formulation is based on the vulnerability index proposed in [7]. The fragility index *IFS* is defined by the weighed sum of 14 parameters related to different features of the construction that influence its behaviour under earthquake loading. Each parameter is assigned to one of four classes (A, B, C and D) of increasing fragility depending on the characteristics of the construction, Table 2. A weight p_i is predefined for each parameter ranging from 0.50 to 1.50 for less to more important parameters, respectively, (Table 2) and the fragility index *IFS* which ranges between 0 and 1 is then obtained from the expression also presented in Table 2.

Parameters P1 and P2 characterize the resisting system of the construction controlling the structural behaviour under earthquakes. These parameters are defined based on the type and quality of the masonry, namely involving data on the material (size, shape and stone type), masonry fabric and arrangement, and level of connection between walls. Parameter P3 is established using a simplified estimate of the shear strength capacity of the construction. Parameter P4 evaluates the level of wall bracing and, implicitly, the risk of out-of-plane collapse. Parameter P5 evaluates the height of the construction and parameter P6 analyses the soil and foundation conditions of the construction. Parameter P7 accounts the potential interaction effects between the construction under analysis and other adjacent buildings. Parameters P8 and P9 evaluate the irregularity in plan and height, respectively, of the construction. Parameter P10 analyses the irregularity of the arrangement of openings in the walls which is important to guarantee efficient load paths. Parameters P11 and P12 analyse the type of horizontal structural systems of the construction, namely by accounting for the level of connection between the floors and the walls and between the roof and the walls. These parameters also account for the additional horizontal loading that floors and/or roofs may apply on the walls. Parameter P13 accounts for the current state of conservation of the structural system and parameter P14 analyses the existence of falling hazards due to non-structural elements that are inadequately connected to the main construction.

After quantifying *IFS*, a fragility class *CFS* is assigned to the construction based on the value of *IFS*. If *IFS* is lower than 0.25, between 0.25 and 0.40, or higher than 0.40, the construction is assigned to a *CFS* class of *Low*, *Moderate* or *High* fragility, respectively. The final step to define the expected level of damage involves a conversion between the *CSF* classification and the damage level which accounts for the selected earthquake scenario. To define the conditions for the three levels of expected damage considered by the framework, mean damage grades [7], which can be connected with the seismic hazard defined by macroseismic intensities (EMS-98 scale) and with the *IFS* values, were rewritten as a function of peak ground acceleration (PGA) values. Three ranges of damage grades were then connected with ranges of *IFS* values representing similar damage conditions (the *CFS* classes) and correlated with specific PGA values representing relevant earthquake scenarios (e.g. the national earthquake zoning). Each range of damage grades was assigned to an expected damage level defined by a colour code (Table 3) and the correlation of damage levels with the *CFS* and the earthquake scenarios was then represented by damage matrices (Table 4). These matrices are the end-user tools defining the expected damage level as a function of a given *CSF* for a selected earthquake scenario with the proposed framework.

Table 2 – Fragility index *IFS* and parameters involved in its quantification

	Parameters	**Fragility Class C_i**				**Weight**	**Fragility index *IFS***
		A	**B**	**C**	**D**	**p_i**	
P1	Type of global structural system	0	5	20	50	0.75	$IFS = \frac{\sum_{i=1}^{14} C_i \cdot p_i}{650}$
P2	Type of masonry of the walls	0	5	20	50	1.00	$(0 \le IFS \le 1.0)$
P3	Lateral strength	0	5	20	50	1.50	
P4	Maximum distance between walls	0	5	20	50	0.50	
P5	Height of the construction	0	5	20	50	1.50	
P6	Soil conditions and foundations	0	5	20	50	0.75	
P7	Interaction with other constructions	0	5	20	50	1.50	
P8	In-plan configuration	0	5	20	50	0.75	
P9	Regularity in elevation	0	5	20	50	0.75	
P10	Alignment of wall openings	0	5	20	50	0.50	
P11	Type of floor structural system	0	5	20	50	1.00	
P12	Type of roof structural system	0	5	20	50	1.00	
P13	Conservation state	0	5	20	50	1.00	
P14	Hazards due to non-structural elements	0	5	20	50	0.50	

Table 3 – Colour code identifying the different expected damage levels

Expected level of damage		
Light	*Medium*	*High*

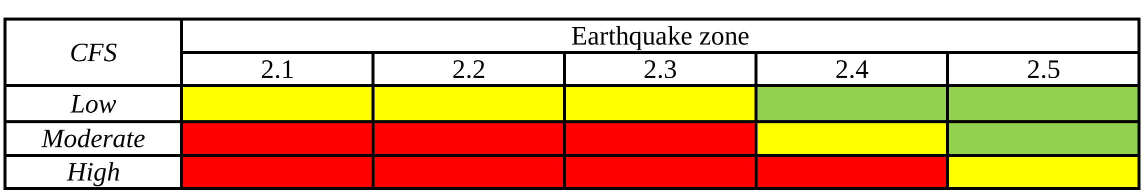


Figure 7 – Example of a damage matrix, adapted from [8].

4.3 Seismic risk analysis of the Church of Santa Maria ad Cryptas

The results of the simplified seismic risk analysis of the Church of Santa Maria ad Cryptas according to the proposed framework are presented herein. The expected level of damage is determined using the procedure detailed in the previous Section and part of the results are then compared with the damages and losses suffered by the church due to the 2009 L'Aquila earthquake. To perform this comparison, the earthquake scenario selected for the analysis is compatible with the 2009 L'Aquila earthquake: a low likelihood event with a PGA around 0.15g at the church site [14]. The damage matrix compatible with that earthquake scenario is that of Fig. 7 for earthquake zone 2.3 [8]. Based on the church data obtained from [12, 13], the parameters needed for the fragility index *IFS* were defined according to Table 4 which lead to a value of *IFS* of 0.27. This value of *IFS* leads to a *CSF* class of *Moderate* fragility and a *High* expected level of damage (Fig. 7). When comparing this level of damage with the actual damage that was observed after the 2009 L'Aquila earthquake, it can be seen there is a good agreement since the damage was reported to be severe [12, 15]. The damage that was observed shows the presence of cracks that ran across the thickness of the north-east and south-west walls, which highlight the separation of the façade from the nave and indicate that an overturning mechanism has developed (Fig. 8). Analogously, the earthquake induced an out-of-plane rotation of the apse's frontal wall, indicated by its detachment from the rest of the structure. The latter damage has probably been enhanced by the presence of dynamic forces coming from the vault. Additionally, the gable of the apse and the belfry have detached and rocked with respect to their base, being removed during post-earthquake shoring operations (Fig. 9). Additional details and a more comprehensive review of these damages is presented in [12, 15].

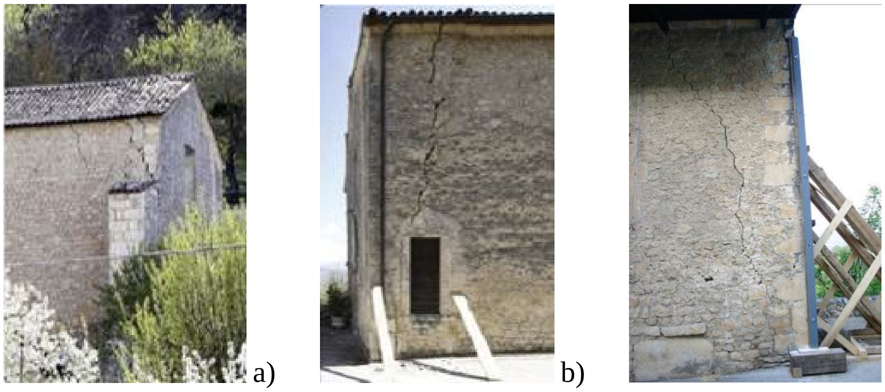
Based on this level of damage, the next step of the framework analyses the reparability of those damages. Although for *High* damage the construction is expected to develop severe structural damage that can make it unstable, given the simplicity of the structural configuration and the type of mechanism that is usually developed in this type of construction, these can be considered to be fully repairable. However, the framework also needs to account for the reparability of the damages to the frescoes that are attached to the building. Due to the severity of the structural damage, the damage to the frescoes are only expected to be partially repairable (Fig. 10). Given these damages, the function of the church is not expected to be easily restored (at the end of 2015, restoration works were still ongoing) and a significant loss of value is foreseen. Based on these considerations, the vulnerability level of the construction is found to be V_V (Fig. 1) which automatically leads to a risk level R_V, no matter the likelihood of the selected earthquake scenario (Fig. 2).

Table 4 – Fragility index *IFS* for the Church of Santa Maria ad Cryptas

Parameters		**Fragility Class C_i**				**Weight**
		A	**B**	**C**	**D**	**p_i**
P1	Type of global structural system				50	0.75
P2	Type of masonry of the walls		5			1.00
P3	Lateral strength		5			1.50
P4	Maximum distance between walls		5			0.50
P5	Height of the construction	0				1.50
P6	Soil conditions and foundations		5			0.75
P7	Interaction with other constructions	0				1.50
P8	In-plan configuration			20		0.75
P9	Regularity in elevation			20		0.75
P10	Alignment of wall openings	0				0.50
P11	Type of floor structural system				50	1.00
P12	Type of roof structural system	0				1.00
P13	Conservation state			20		1.00
P14	Hazards due to non-structural elements			20		0.50

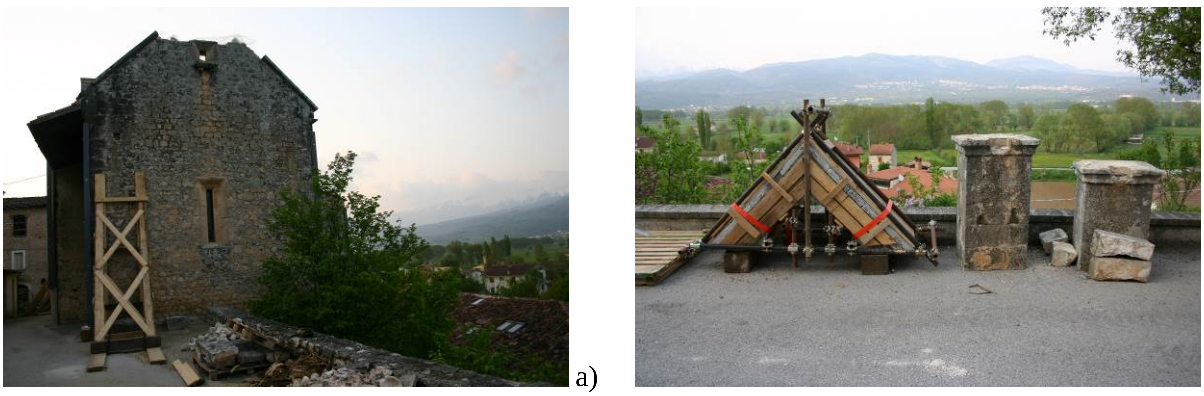
Fragility index *IFS*

$$IFS = \frac{\sum_{i=1}^{14} C_i \times p_i}{650} = 0.27$$



a) b) c)

Figure 8 – Damages suffered by the Church of Santa Maria ad Cryptas during the L'Aquila earthquake: detachment of the façade from the walls of the nave a) and b); detachment of the apse frontal wall from the rest of the structure c).



a) b)

Figure 9 – Damages suffered by the Church of Santa Maria ad Cryptas during the L'Aquila earthquake: damage to the gable of the apse a); belfry removed during post-earthquake interventions b).

Figure 10 – Damages suffered by the frescoes of the Church of Santa Maria ad Cryptas during the L'Aquila earthquake.

5. Final remarks

The simplified risk assessment framework proposed herein can be used as a screening procedure for the preliminary assessment of a large number of cultural heritage assets with limited resources or for the preliminary identification of assets that require a more refined and resource demanding risk evaluation. The procedure involves a qualitative risk analysis based on a series of structured questionnaires addressing the main components of a risk analysis: the likelihood of the hazard, the consequences of the hazard, the vulnerability and the loss of value of the asset and, finally, the capacity to recover from the event.

The general framework was further detailed by developing specific damage assessment forms and guidelines for the case of seismic risk [8]. In this context, specific procedures were developed to analyse the expected level of damage for four types of cultural heritage masonry constructions. The main aspects of these procedures were described and an illustrative application for the Church of Santa Maria ad Cryptas in Italy was also presented. Comparable results of this application were found to be in agreement with the damages suffered by this church during the 2009 L'Aquila earthquake. Further refinements of the proposed framework are expected to be developed in the near future to include more types of constructions as well as to define similar guidelines for other types of hazards.

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