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# DEFINITION OF MULTI-HAZARD VULNERABILITY INDICATORS FOR CULTURAL HERITAGE BUILDINGS

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## Abstract

*The Sendai Framework for Disaster Risk Reduction recognizes the importance of cultural heritage for society and emphasize the need to assess their vulnerability from multiple hazards. Developing adequate multi-hazard vulnerability assessment processes is fundamental to this end. Still, given the large number of cultural heritage assets that can be exposed to different hazards in a region, the development of simplified multi-hazard approaches that can provide an initial risk screening of multiple assets to identify the need for more detailed analyses plays a central role for prioritization.*

*In this context, we propose an index-based multi-hazard vulnerability assessment methodology for churches, able to consider vulnerability from earthquakes, floods, and fire. The proposed multi-hazard index has been obtained by combining a series of indicators, defined by performing a literature review. The indicators were selected due to their relevance for the vulnerability classification of the assets but also their ability to be easily scored from remotely sensed data or fast in situ screening. The presented research describes in detail each indicator and provides insights on how they should be scored and integrated to obtain the overall multi-hazard vulnerability index for churches. The vulnerability indicators constitute the primary component of a five-step, multi-hazard vulnerability assessment methodology that can be flexibly applied as a prioritization method to rapidly screen multiple assets and identify the most vulnerable churches that may require a more detailed assessment. The methodology is tested on a series of case study applications in Portugal and Italy.*

**Keywords:** Cultural Heritage, Churches, Multi-hazard Taxonomy, Earthquake Flood, Fire.

## 1 INTRODUCTION

The Sendai Framework for Disaster Risk Reduction [1] recognizes the importance of cultural heritage for society, thus emphasizing the need to assess the impact that potential hazards may have on the built cultural heritage. Developing adequate multi-hazard vulnerability assessment and risk management processes is fundamental to this end. Still, given the large number of cultural heritage assets that are exposed to different hazards, the development of simplified multi-hazard approaches that can provide an initial risk screening of multiple assets plays a central role in prioritization, allowing the decision maker to identify the assets where to further invest in more detailed risk analyses [2].

Internationally, in the last decade, there has been an increasing attention for multi-hazard and multi-risk, and for the impacts resulting from compound and consecutive disasters [3]–[6]. Many regions of the world are prone to multiple types of potentially interacting and overlapping natural hazards and only through an analysis of all the relevant threats, an effective risk reduction can be carried out [7]. Moreover, the risk of consecutive disasters will increase due to growing exposure, the interconnectedness of human society, and the increased frequency and intensity of nontectonic hazards [8]. The adverse impacts on lives and livelihoods, and regional and local economies are felt more and more. Losses to both tangible and intangible cultural heritage during these disasters are increasing as well. These losses include those to sites, structures and artifacts of cultural significance, as well as impacts to cultural tourism and the financial resources these sites introduce to local communities [9].

There have been various multi-hazard vulnerability assessment studies published in literature, each with their own unique perspectives and applications. Papathoma-Köhle et al. [10] created an index for dynamic flooding in mountain areas demonstrating the transferability of vulnerability assessment approaches between hazard types, reducing the amount of required data and offering a tool that can be used in areas where empirical data are not available. Kappes et al. [11] adapted the indicator-based tsunami vulnerability assessment indicator PTVA by Papathoma [12] to be applicable in a multi-hazard context. In their case study the vulnerability of buildings to debris flows, shallow landslides, and river flooding for emergency planning and for general risk reduction purposes is assessed. The implementation of the methodology leads to reasonable results indicating the vulnerable buildings and supporting the priority setting of different end-users according to their objectives. The study of Gentile et. al [13] focus on scoring, selecting, and developing physical fragility and multi-hazard vulnerability models for assets of interest, with particular emphasis on buildings. The approach is demonstrated for the buildings of the virtual urban testbed ‘Tomorrowville’, considering earthquakes, floods, and debris flows as case-study hazards. Moreover, the exposure and vulnerability assessment of different assets from a multi-hazard perspective is the main goal behind the development of the global exposure database for all (GED4ALL [14]). It covers several assets, including buildings, roads, railways, and lifelines, and it was developed considering earthquakes, volcanoes, floods, tsunamis, storms, cyclones, and drought.

Despite the increasing attention to this topic, the literature on cultural heritage multi-hazard vulnerability assessment, and specifically churches, is limited. Several authors addressed this topic from a single hazard perspective focusing on earthquake [15]–[22], flood [23], [24], fire [9], [25], [26], and windstorm [27], among others. However only few authors investigated the topic from a multi-hazard point of view. Sevieri et al. [28] introduced a multi-hazard risk prioritization framework specifically developed for cultural heritage assets. The proposed framework relies on a multilevel rapid-visual-survey (RVS) form for the multi-hazard exposure data collection and risk prioritization of case-study assets. The collected data are used for the computation of seismic- and wind-risk prioritization indices, specifically calibrated for cultural heritage assets with various structural and non-structural features. Julià and Ferreira [29] contributed to paving the way towards the establishment of future multi-hazard vulnerability and risk assessment methodologies for Historic Urban Areas by offering a comprehensive review of some of the most relevant methodologies proposed to date in this research area.

In Europe, a significant portion of cultural heritage structures are churches [30]. Assessing the vulnerability of churches under a multi-hazard perspective is crucial for the preservation of cultural heritage buildings and the safety of the people who use them. Churches are not only religious and historical landmarks but also cultural and social assets that hold a significant place in the community. By identifying vulnerabilities and developing appropriate strategies to reduce multiple risks, the community can protect these valuable assets and ensure their continuity for future generations. However, there is a noticeable lack of attention from the scientific community towards this topic. This gap in knowledge and research motivated to delve into this area and try to develop an indicator-based methodology for the multi-hazard vulnerability assessment of churches.

The focus of this paper is on the multi-hazard vulnerability assessment of churches, which is achieved through the development of an indicator-based methodology. The proposed methodology can contribute towards the assessment of the impact of multiple hazards (fires, earthquakes, and floods) on cultural heritage buildings, and establish a first basis for further research in this field. Furthermore, the methodology can be a flexible prioritization method that can be applied as a basis for the fast screening of multiple assets.

The research is presented as follows. Section 2 focuses on the selection of churches vulnerability indicators for fires, earthquakes, and floods and details the review process that informed the selection. Section 3 outlines the vulnerability assessment methodology and provides a step-by-step guide for its application. Section 4 introduces two case study areas in Marche Region, Italy, and in the city of Porto, Portugal, where the methodology has been tested. Section 5 presents the results of the case study applications. In conclusion, Section 6 synthesizes the findings presented throughout the paper and offers an open discussion on the potential field of application of this methodology and its future developments.

## 2 MULTI-HAZARD VULNERABILITY INDICATORS FOR CHURCHES

In this section, the selected churches vulnerability indicators for each of the considered hazards are introduced. Fire, earthquake, and flood have been selected as a first set of hazards to investigate, because of the following two reasons:

1. Authors expertise encompasses earthquake, flood and fire risk assessment and management.
2. Most of the available literature on cultural heritage vulnerability assessment focuses on these three hazards.

Nevertheless, the proposed approach can be easily expanded in the future to cover other hazards, such as windstorms or landslides.

The choice of indicators is a key element for the development of the overall methodology (Section 3) and must be designed to align with the overall methodological aim: they should be easily obtainable and provide a comprehensive view of the building's vulnerability from different hazards. For each hazard, a subset of those usually adopted to perform the vulnerability assessment from a single hazard perspective has been selected since the procedure does not intend to replace them but instead outline a multi-risk prioritizing procedure. The source of the data (remote assessment or in-situ survey) is also a key factor, as it impacts the speed of the screening process, and therefore, the overall rapidity of the assessment. The final list of the selected vulnerability indicators for earthquake, flood and fire are reported in Table 1.

| ID | Indicator name | Source | Diff. level | References |
|---|---|---|---|---|
| | *Earthquake indicators* | | | |
| **EQ.1** | Height of the surrounding buildings - interaction with adjacent buildings | Remote and in-situ | 1 | [11], [19], [29], [31] |
| **EQ.2** | Height of the church | Remote and in-situ | 1 | [11], [15], [19] |
| **EQ.3** | Quality of the masonry | In-situ survey | 2 | [11], [15], [18], [19] |
| **EQ.4** | Roof condition | In-situ survey | 2 | [15]–[17], [19], [29] |
| **EQ.5** | Predominance of in-plane or out-of-plane mech. | In-situ survey | 2 | [19], [32] |
| **EQ.6** | Openings of wall façade | In-situ survey | 1 | [19], [31] |
| **EQ.7** | Type of soil | In-situ survey | 2 | [19] |
| **EQ.8** | Site morphology | In-situ survey | 2 | [18], [19] |
| **EQ.9** | General external state of conservation | In-situ survey | 1 | [19] |
| **EQ.10** | Bell tower presence | Remote and in-situ | 1 | [19], [33] |
| | *Flood indicators* | | | |
| **FL.1** | Number of floors | In-situ survey | 1 | [11], [23], [34] |
| **FL.2** | Dry feature of the masonry | In-situ survey | 2 | |
| **FL.3** | Opening of wall facade on the first floor | Remote and in-situ | 1 | |
| **FL.4** | Quality of the drainage system | Remote and in-situ | 2 | |
| **FL.5** | Number of exposed facades | Remote and in-situ | 1 | |
| **FL.6** | Protection by vegetation | Remote and in-situ | 1 | [11] |
| **FL.7** | Type of soil | In-situ survey | 2 | |
| **FL.8** | Slope of the ground | Remote and in-situ | 1 | |
| | *Fire indicators* | | | |
| **FI.1** | Electric Installations | In-situ survey | 2 | [26] |
| **FI.2** | Gas installations | In-situ survey | 2 | [26] |
| **FI.3** | Distance of the surrounding buildings | Remote and in-situ | 1 | |
| **FI.4** | Exterior hydrants | Remote and in-situ | 1 | [26] |
| **FI.5** | Automatic extinguish system | In-situ survey | 1 | [26] |
| **FI.6** | Active suppression system | In-situ survey | 1 | [26] |
| **FI.7** | Presence of vegetation | Remote and in-situ | 1 | [26] |
| **FI.8** | Security cameras for intentional fires | In-situ survey | 1 | |
| **FI.9** | Average occupancy | Remote and in-situ | 1 | . |
| **FI.10** | Building content | Remote and in-situ | 1 | [26] |
| **FI.11** | Open flames | Remote and in-situ | 1 | |

Table 1: List of the selected churches vulnerability indicators for earthquake, flood, and fire

For each indicator, together with the ID, name, and references, the following fields have been added:

- ‘Source’, that indicates the different sources of information that can be used to assess the considered indicator, including remote assessments or in-situ surveys.
- ‘Diff. level’, that indicates the level of difficulty in compiling and elaborating such information. Value ‘1’ means that non experts can easily assess the indicator, while value ‘2’ refers to the case where only experts can reliably assess the indicator.

Each indicator can assume a discrete vulnerability level, ranging from zero to three. Zero represents the best case, where the indicator has no influence on the vulnerability of the church. Three represents the worst case, where the element under evaluation is in poor conditions and can significantly increase the church vulnerability. The characterization of the different levels was informed by hazard-specific literature. As an example, a selection of vulnerability indicators and the description of the different levels they can assume is reported in Table 2.

| Indicator | Vuln. level | Description |
|---|---|---|
| **EQ.1**<br>Height of the surrounding buildings - interaction with adjacent buildings | 0 | No one buildings are close enough and tall enough to potentially collapse on the church. The interaction with adjacent/connected buildings is considered negligible in altering the seismic response of church. |
| | 1 | At least one side of the church can be damaged by the collapse of a neighbourhood building. The interaction with adjacent/connected buildings is considered small to moderate in negatively altering the seismic response of church. |
| | 2 | At least two sides of the church can be damaged by the collapse of a neighbourhood building. The interaction with adjacent/connected buildings is considered moderate to high in negatively altering the seismic response of church. |
| | 3 | At least three sides of the church can be damaged by the collapse of a neighbourhood building. The interaction with adjacent/connected buildings is considered very high in negatively altering the seismic response of church. |
| **EQ.10**<br>Bell tower presence | 0 | The bell tower is not present |
| | 3 | The bell tower is present |
| **FL.6**<br>Protection by vegetation | 0 | The building is surrounded from vegetations that, in case of flood, will decrease the velocity of the water and block the transported materials |
| | 1 | No presence of vegetation around the building / the building is surrounded from an irrelevant density of vegetation |
| | 2 | The building is surrounded by low vegetation/bushes that, in case of flood, can be carried together with the flow slightly increasing the damage to the building |
| | 3 | The building is surrounded by tall vegetation that, in case of flood, can be carried together with the flow significantly increasing the damage to the building |
| **FI.10**<br>Building content | 0 | The content is not flammable |
| | 3 | The content is flammable |

Table 2: Examples of earthquake, flood and fire vulnerability indicators and description of the different levels, from zero to three, that they can assume

Most indicators were assigned four vulnerability levels, with some exceptions. As also shown in Table 2, there are some indicators, such as ‘EQ.10 Bell tower presence’, which require a binary evaluation, such as 'present'/'not present'. Therefore, only two levels of vulnerability are needed.

A detailed description of each vulnerability indicator provided in Table 1, and all the values that can assume, similarly to what has been reported as a sample in Table 2, is available at: https://github.com/silviadeangeli/Churches_MultiHazard_Vulnerability.

## 3 A MULTI-HAZARD VULNERABILITY ASSESSMENT METHODOLOGY FOR CHURCHES

The vulnerability indicators for churches, as described in Section 2, constitute the primary component of a five-step, multi-hazard vulnerability assessment methodology, as illustrated in Figure 1. This methodology can be flexibly applied as a prioritization method to rapidly screen multiple assets and identify the most vulnerable churches that may require a more detailed assessment from a multi-hazard perspective. In this section, the methodology is introduced, together with a step-by-step guide for its application.

Figure 1: The five steps of the multi-hazard vulnerability assessment methodology for churches

### 3.1 Step 1. Identification of the study area and the relevant hazards

The first step in conducting a cultural heritage assessment is to determine the localization and extent of the area to be investigated, which significantly impacts the time and effort required to complete the assessment. This aspect is closely related to the study's ultimate goal. Cultural heritage assessment and prioritization can be commissioned on different administrative units or specific areas within administrative boundaries, spanning municipal, regional, or national scales.

Once the relevant administrative units have been identified based on the study's objective, all potential hazards must be identified using historical records or existing hazard analyses. It is crucial to consider the increasing frequency of disasters in areas previously not considered at risk due to climate change.

### 3.2 Step 2. Selection of churches inside the study area

Once the extent of the study area has been determined (Step 1), all the cultural heritage buildings located within it need to be identified and geolocated. The methodology presented in this study has been specifically developed for masonry churches, so these buildings must be selected accordingly. However, this approach can be generalized in the future to include other cultural heritage buildings, such as museums or religious buildings other than churches.

Geolocating the churches allows you to determine the potential hazards that each of them face by interpolating available hazard maps and analyzing past hazard events (see Step 1). It also allows to identify the physical and social context in which the church is situated, such as whether it is in an urban or rural area, a densely populated area, or a tourist area.

This information represents the basis to prioritize the churches based on their level of exposure and vulnerability to natural hazards, as well as their cultural and historical significance, to determine which buildings require more urgent protection and conservation measures.

Overall, geolocating cultural heritage buildings such as churches is a crucial step in the process of assessing their vulnerability to natural hazards and developing effective risk mitigation strategies to preserve these important assets for future generations.

### 3.3 Step 3. Assessment of the vulnerability indicators

In Step 3 of the methodology, a multi-hazard index-based vulnerability assessment is conducted for each identified church (see Step 2). Vulnerability levels ranging from zero to three are assigned to each hazard indicator listed in Table 1. The vulnerability sheet can be compiled using information obtained remotely or through on-site surveys by both experts and non-experts. This step represents the core of the overall methodology.

The level of uncertainty associated with the final vulnerability assessment depends heavily on the experience of the compiler. In the case of an expert compiler, vulnerability levels can be assigned with a high degree of confidence, and only one level out of the four possibilities can be chosen assigning it a 100% probability. This is referred to as a 'deterministic' assessment.

However, if the compiler is not sufficiently expert or the survey does not allow to have sufficient confidence in the assessment of the vulnerability level, it is reasonable to introduce uncertainty into the methodology by assigning a certain probability to each vulnerability level. This is referred to as a 'probabilistic' assessment.

The 'deterministic' assessment can then be seen as a special case of the more general 'probabilistic' assessment, where 100% probability is assigned to only one level for all considered indicators. The effect of uncertainty on the vulnerability assessment has been tested in case studies presented in Section 4.

### 3.4 Step 4. Weighting and combination of the indicators in a multi-hazard vulnerability index

The global multi-hazard vulnerability index $I_{MH}$ for each church can be generically computed according to eq. (1):

$$I_{MH} = \sum_{h=1}^{n} (I_h \cdot w_h) \tag{1}$$

Where: $h$ is the considered hazards, $n$ is the number of hazards considered, $I_h$ is the single hazard vulnerability indicator, and $w_h$ is the weight attributed to each hazard with $\sum_{h=1}^{n} w_h = 1$.

Each single hazard vulnerability indicator $I_h$ is computed as a weighted sum of the values assumed by every single indicator, according to eq. (2)

$$I_h = \sum_{i=1}^{m} (w_i * \sum_{v \in L_i} (v * P_V^i(v))) \tag{1}$$

Where: $i$ is each of the considered hazard indicators for hazard $h$, $m$ is the number of indicators considered for hazard $h$, $w_i$ is the weight attributed to each indicator $i$ with $\sum_{i=1}^{m} w_i = 1$, $L_i$ is the vector of the different discrete vulnerability levels $v$ for the indicator $i$, $P_V^i(v)$ is the Probability Mass Function of the vulnerability levels $v$.

In this current stage of development of the methodology we focused on three specific hazards (*n=3:* earthquake, flood, and fire) and we assumed to assign the same importance to each of them. Therefore, eq. (1) and (2) can be further simplified, assuming the final formulations expressed respectively by eq. (3) and (4a), (4b), (4c):

$$I_{MH} = \frac{I_{EQ}+I_{FL}+I_{FI}}{3} \tag{3}$$

Where $I_{EQ}$ is the earthquake vulnerability index, $I_{FL}$ the flood vulnerability index, and $I_{FI}$ the fire vulnerability index, calculated as:

$$I_{EQ} = \sum_{i=1}^{10}(w_{EQ_i} * \sum_{v\in L_i}(v * P_V^{EQ_i}(v))) \tag{4a}$$

$$I_{FL} = \sum_{i=1}^{8}(w_{FL_i} * \sum_{v\in L_i}(v * P_V^{FL_i}(v))) \tag{4b}$$

$$I_{FI} = \sum_{i=1}^{11}(w_{FI_i} * \sum_{v\in L_i}(v * P_V^{FI_i}(v))) \tag{4c}$$

The weights associated with each indicator, as reported in Table 3, have been assigned on an expert judgment informed by the analyzed vulnerability literature.

| ID | Indicator name | Weight |
|---|---|---|
| **EQ.1** | Height of the surrounding buildings | 0,15 |
| **EQ.2** | Height of the church | 0,15 |
| **EQ.3** | Quality of the masonry | 0,1 |
| **EQ.4** | Roof condition | 0,1 |
| **EQ.5** | Predominance of in-plane or out-of-plane mechanisms | 0,1 |
| **EQ.6** | Openings of wall façade | 0,05 |
| **EQ.7** | Type of soil | 0,05 |
| **EQ.8** | Site morphology | 0,1 |
| **EQ.9** | General external state conservation | 0,1 |
| **EQ.10** | Bell tower presence | 0,1 |
| **FL.1** | Number of floors | 0,18 |
| **FL.2** | Dry feature of the masonry | 0,09 |
| **FL.3** | Opening of wall facade on the first floor | 0,14 |
| **FL.4** | Quality of the drainage system | 0,09 |
| **FL.5** | Number of exposed facades | 0,09 |
| **FL.6** | Protection by vegetation | 0,09 |
| **FL.7** | Type of soil | 0,14 |
| **FL.8** | Slope of the ground | 0,18 |
| **FI.1** | Electric Installations | 0,1 |
| **FI.2** | Gas installations | 0,1 |
| **FI.3** | Distance of the surrounded building | 0,05 |
| **FI.4** | Exterior hydrants | 0,1 |
| **FI.5** | Automatic extinguish system | 0,1 |
| **FI.6** | Active suppression system | 0,15 |
| **FI.7** | Presence of vegetation | 0,05 |
| **FI.8** | Security cameras for intentional fires | 0,05 |
| **FI.9** | Building content | 0,01 |
| **FI.10** | Open flames | 0,15 |
| **FI.11** | Average occupancy | 0,05 |

Table 3: List of the vulnerability indicators for earthquake, flood, and fire and their corresponding weights

### 3.5 Step 5. Analysis and interpretation of the results

The result of this methodology is a multi-hazard vulnerability index $I_{MH}$, representing the average vulnerability of the building based on the hazards considered. While this value can provide a general idea of the building's overall vulnerability, it can be difficult to directly use its absolute value as a criterion for prioritization. In other words, it would be quite challenging to identify a vulnerability threshold above which we can consider a church as vulnerable, and therefore needing a deeper assessment.

Nevertheless, the multi-hazard vulnerability index $I_{MH}$ can be used to rank the assets from the most to the least vulnerable, identifying the first set of buildings that would require a deeper assessment. As a second step, it is then possible to evaluate which hazard contribute most to the overall vulnerability of each church analyzing the global multi-hazard vulnerability index $I_{MH}$ in comparison with the single hazard indices $I_{EQ}, I_{FL}$ and $I_{FI}$. By examining the specific hazard indicators, the expert will have a clear understanding of which hazard poses the greatest threat, providing valuable information for decision-making.

## 4 ITALY AND PORTUGAL CASE STUDIES

In this section, two case studies will be presented to demonstrate the applicability of the proposed methodology in different geographic contexts. The first case study includes two churches located in Porto, Portugal, while the second examines three churches in the Marche region, Italy. These two areas have been selected due to their high exposure to booth flood and seismic hazards. Additionally, these two case studies are representative of two different urban and social contexts, since the churches in Porto are in densely populated touristic areas, while in the Marche case study churches are in rural villages or not densely urbanized areas.

Applying the methodology described in Section 3, the overall multi-hazard vulnerability of all these five churches has been evaluated. The vulnerability sheets have been compiled using information obtained by on-site visits simulating the compiling of both experts and non-experts, i.e., performing both a 'deterministic' and ‘probabilistic’ assessment (see Section 3.3). In such a way, it has been possible to evaluate the effect of the uncertainty in the estimation of the different vulnerability indices on the overall vulnerability assessment.

### 4.1 Porto case study

Porto region is highly susceptible to flood hazard [35], [36], and around 50% of all occurrences are concentrated in the Porto Metropolitan Area, mainly the Porto city center and nearby riverside areas of the Douro River [37].

The two churches selected in the case study area, the Capela das Almas, and the Igreja de Santo Ildefonso, are depicted in Figure 2. Both churches are situated in high-density urban areas. The Capela das Almas is located on the busy commercial street of Rua de Santa Catarina, while the larger Igreja de Santo Ildefonso is situated in an elevated part of the city. These two churches serve active functions inside the urban context of the city of Porto. The Capela das Almas is a popular attraction for both locals and visitors, offering services that can be attended without any charge. Santo Ildefonso is also active for services but requires a fee for visiting and houses a museum within the church. Both churches attract people throughout the year and possess valuable content within their walls. Santo Ildefonso is adorned with ornate gold and wood furnishings, while Capela das Almas has its own unique character, with significant wood furnishings.

Despite being Porto a city frequently affected by floods, these churches did not sustain any damage during the devastating flood event of January 2023. This allowed for a thorough analysis of both the interior and exterior of the buildings.

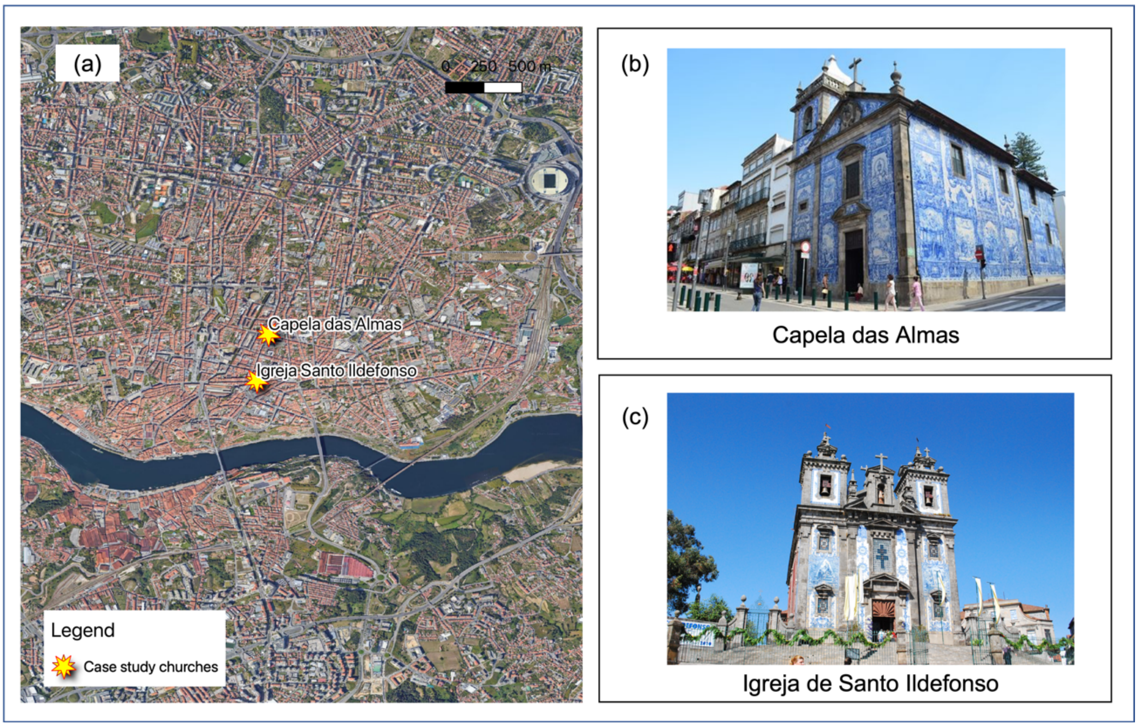

Figure 2: Case study churches located in the city of Porto, Portugal: (a) geolocation of the two churches; (b) exteriors of Capela das Almas; (c) exteriors of Igreja de Santo Ildefonso.

### 4.2 Marche region case study

On September 15th, 2022, the region was hit by a storm system that originated on the Tyrrhenian side of the peninsula. Initially, the phenomena affected the central-northern mountainous and high-hill areas of the region. Later in the afternoon, a self-regenerating and stationary system formed, affecting not only the inland areas but also the hilly and coastal part of the province of Ancona. Heavy rainfall caused a rapid rise in the hydrometric levels of several basins, including Candigliano, Cesano, Misa, and Sentino, leading to exceeding the alarm threshold levels in different sections and widespread flooding [38]. Among others, the city of Senigallia, where one of the case study churches is located, was flooded, causing severe damages.

On November 9th at 7:07 a.m., an earthquake of magnitude Ml 5.7 (Mw 5.5) was recorded by the Italian Seismic Network. The epicenter was in the sea, about 30 km from the Marche coast in the province of Pesaro Urbino. The churches in the earthquake-affected area sustained physical damage both inside and outside.

The three churches selected in the case study area are depicted in Figure 3. The Church of SS. Vincenzo and Anastasio in Roncosambaccio (Figure 3, panel (b.1)) is in the internal part of the Marche’s region and it has been externally damaged by the earthquake, as illustrated in Figure 3, panel (b.2). The church, located on a hill, has suffered from seismic waves amplification. Although it was impossible to access the interior of the church, a local team of experts was able to enter a few days after the earthquake, and a video inspection has been available to support the assessment of some of the vulnerability indicators from remote.

The Sanctuary of Santa Maria Goretti in Coronado (Figure 3, panel (c.1)), is located on the top of a hill. The church show significant damages on the external masonry and signs of humidity are presents on the bottom of the building. Moreover, the church is connected with another building on one side, as shown in Figure 3, panel (c.2). This structural layout can play an important role in case of earthquake due to pushing actions that may arise in consequence to bad connections between the two elements.

The Senigallia Cathedral (Duomo di Senigallia, in Italian; Figure 3, panel (d)) is in Senigallia city center, close to the Misa River. The church has been impacted by booth flood and earthquake events. During the field-survey conducted in January 2023, the church showed a significant presence of humidity in the bottom part of the building. Moreover, the church showed some cracks on the outside of the building.

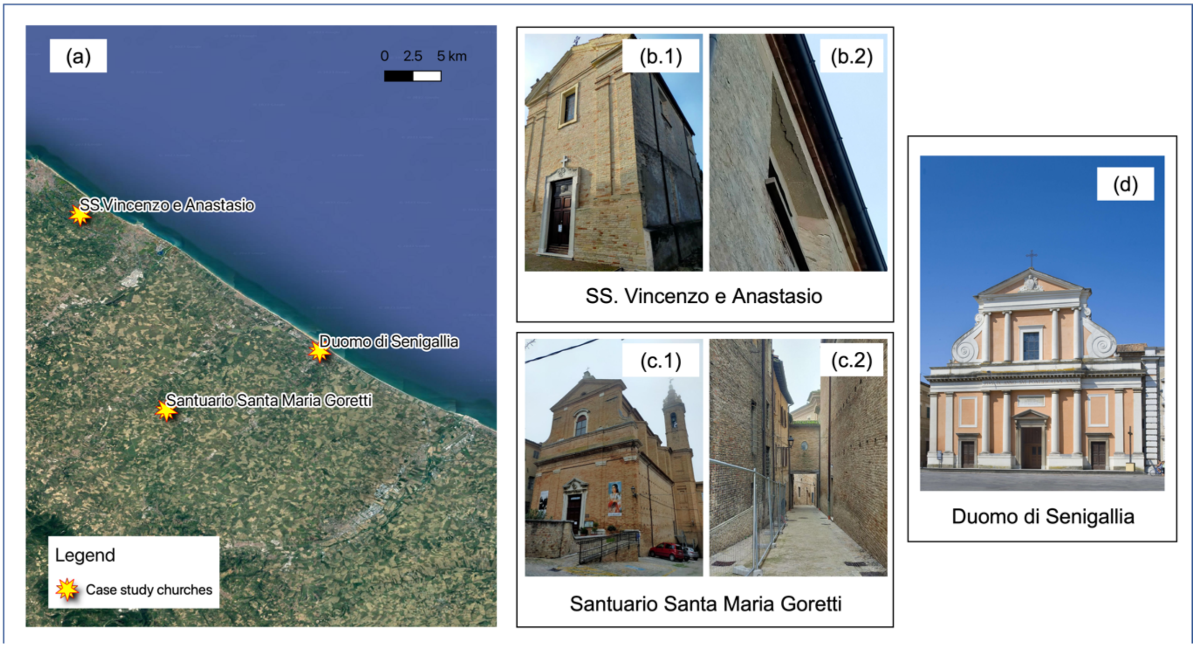

Figure 3: Case study churches located in Marche region, Italy: (a) geolocation of the three churches; (b.1-2) exteriors of SS. Vincenzo e Anastasio; (c.1-2) exteriors of Santuario di Santa Maria Goretti; (d) exteriors of Duomo di Senigallia.

## 5 RESULTS AND DISCUSSION

Using the methodology described in Section 3, we conducted an overall multi-hazard vulnerability assessment of the five churches introduced in Section 4. We compiled vulnerability sheets by gathering information from on-site surveys simulating the compiling of both experts and non-experts, i.e., performing both a 'deterministic' and ‘probabilistic’ assessment. The results of the assessment are summarized in this section, and some examples are given below.

Figure 4 shows the resulting fire vulnerability index $I_{FI}$ (deterministic) for two of the case studies, ‘Duomo di Senigallia’ and ‘Capela das Almas’. Although the index is similar for the two churches in absolute value, the use of multiple indicators with different weights (see eq. (2)) allows for a distinction among the main vulnerability factors that concurred to obtain the overall fire vulnerability value. For example, the presence of exterior hydrants (FI.4) and security cameras (FI.8) plays a role in the fire vulnerability of ‘Capela das Almas’, while they are completely not relevant in the case of ‘Duomo di Senigallia’. This information can help in targeting mitigation efforts in resource-limited situations.

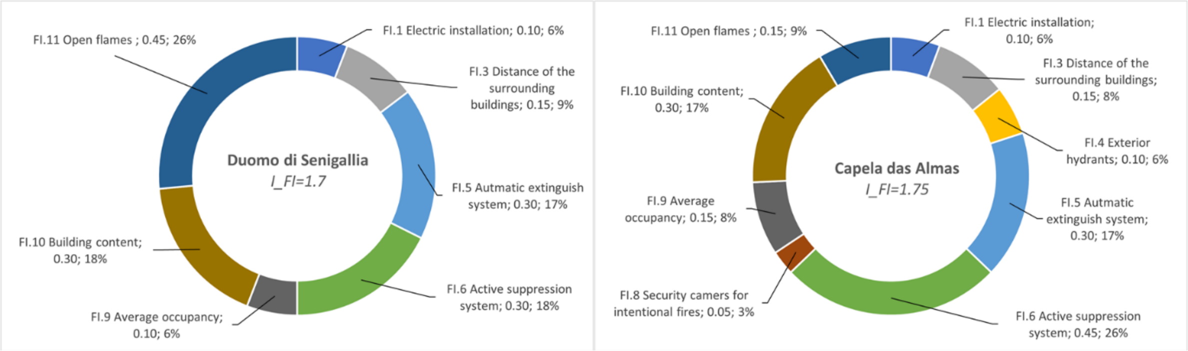

Figure 4: Comparison between the deterministic fire vulnerability index $I_{FI}$ for 'Duomo di Senigallia' and 'Capela das Almas'. The figure shows how the methodology can highlight different sources of vulnerability by investigating the role of different indicators.

The spider diagram depicted in Figure 5 compares the overall values of the deterministic multi-hazard vulnerability index $I_{MH}$ with the individual hazard indices $(I_{EQ}, I_{FL}, I_{FI})$ that compose them for all the five case study churches.

Noteworthy is the comparison between 'Duomo di Senigallia' and 'SS. Vincenzo ed Anastasio': although the two deterministic $I_{MH}$ values are not so different (1.52 and 1.22 respectively), the contribution of the different hazards is significantly different. In the first case, the church is homogeneously exposed to the three considered hazards, and there is no evidence of a dominant hazard, on which it would possibly be a priority to intervene to significantly reduce the vulnerability. In the second case, the fire vulnerability index $I_{FI}$ turns out to be decidedly dominant. In case a decision maker wanted to intervene to significantly reduce the overall vulnerability, the analysis suggests acting on the fire hazard as a priority. An action to reduce flood vulnerability, which is already low, for example, would have a limited impact on the overall vulnerability of that church.

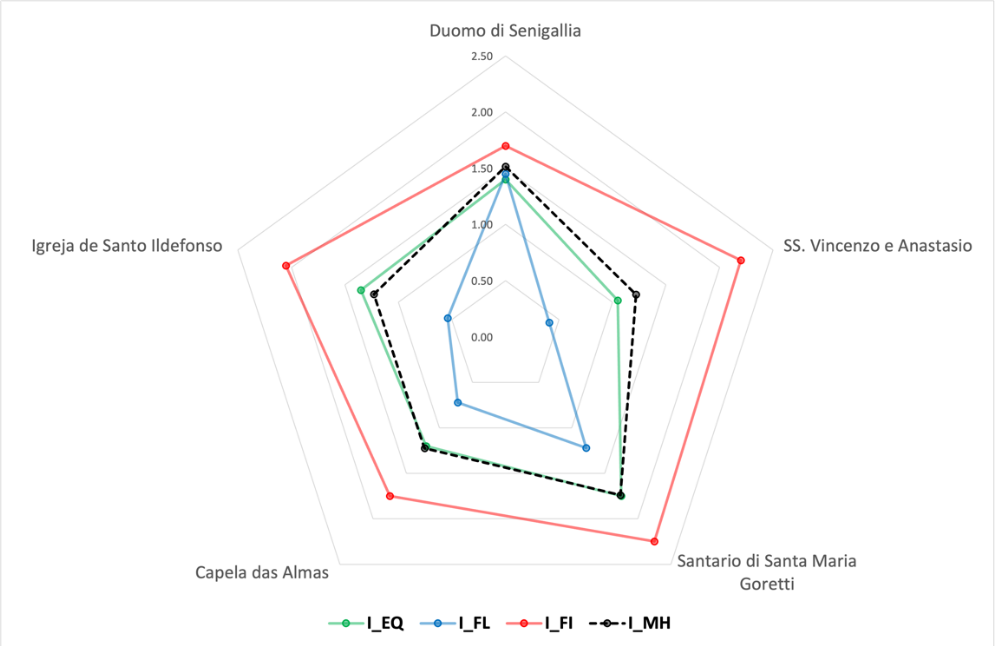

Figure 5: Spider diagram showing the values of the deterministic multi-hazard vulnerability index $I_{MH}$ and the individual hazard indices $I_{EQ}, I_{FL}, I_{FI}$ for all the five case study churches. The figure makes it possible to compare the relative importance of the different hazards in forming the overall index.

Finally, a comparison of $I_{MH}$ estimates by deterministic and probabilistic approaches is shown in Figure 6. The figure shows that the methodology is sufficiently robust even to possible uncertainties in the evaluation of the different indicators, highlighting its potential to be widely used also by non-experts. In fact, variations in $I_{MH}$ are small and are not such as to upset the ranking among the vulnerabilities of the different exposed elements considered. This turns out to be an extremely important feature of the methodology in the case of using the indices to hierarchize vulnerability mitigation interventions.

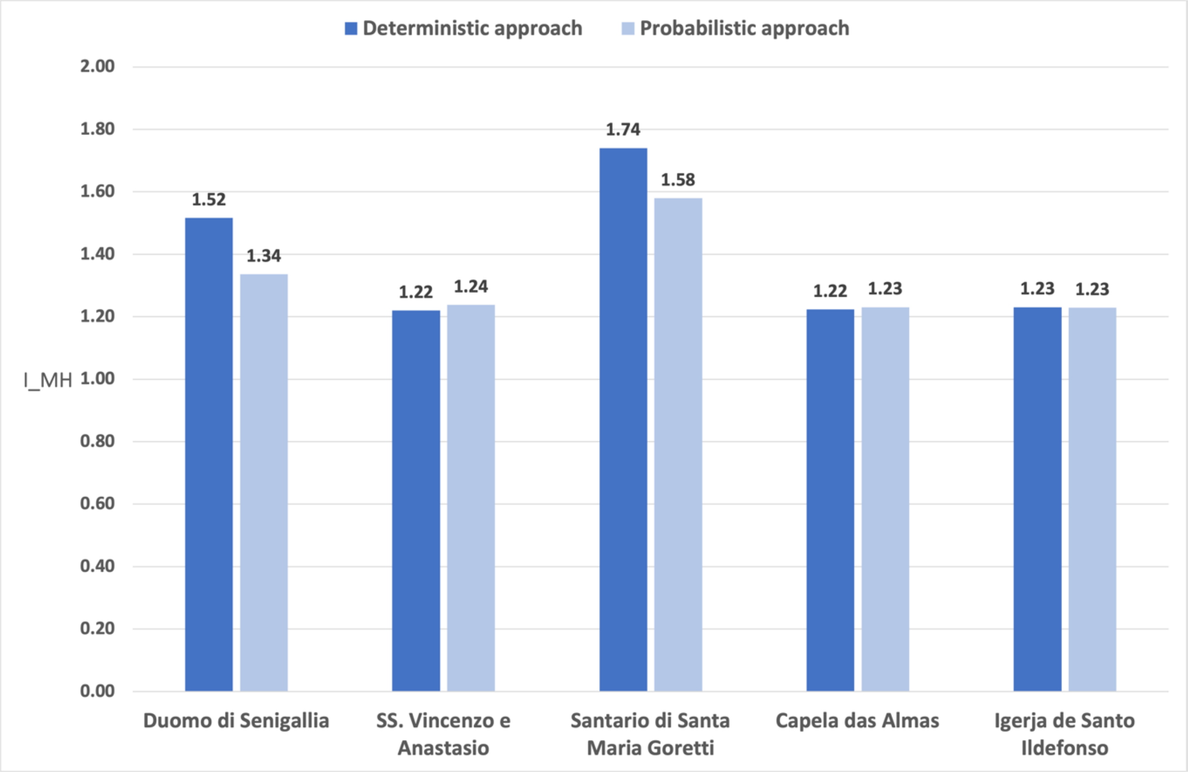

Figure 6: Comparison of the multi-hazard vulnerability indices $I_{MH}$ for different case studies evaluated using deterministic (dak blue) and probabilistic (light blue) approaches.

## 6 CONCLUSIONS

Assessing the vulnerability of churches under a multi-hazard perspective is crucial for their preservation and the safety of the people who use them. Churches are not only important religious and historical landmarks, but they are also significant cultural and social assets within the communities. Despite the large number of cultural heritage sites exposed to different hazards all over the world, in the literature there is a lack of multi-hazard approaches specifically developed for cultural heritage buildings.

To address this need, we proposed an indicator-based methodology for the multi-hazard vulnerability assessment of churches which currently considers the vulnerability from earthquakes, floods, and fire. Our approach combines a series of indicators that have been selected based on their relevance to the vulnerability classification of the assets and their ability to be easily scored using remotely sensed data or through fast in situ screening. The vulnerability assessment is robust enough to be performed by both experts and non-experts, without introducing much uncertainty in the overall vulnerability assessment.

The applicability of the methodology has been tested on five churches located in two different geographic contexts (Italy and Portugal), highlighting its validity at least in the Mediterranean area.

Further developments would include: (i) other hazards, such as windstorm or landslides; (ii) other cultural heritage buildings, such as museums or religious buildings other than churches, (iii) case studies in other countries. Of course, if highlighted by those wider applications, possible refinements of the list of selected indicators will be carried out as well.

By introducing this methodology, this work aims to contribute towards the assessment of the impact of multiple hazards on cultural heritage buildings and establish a foundation for further research in this field. Furthermore, the methodology aspires to become a valuable and practical tool for the scientific community, by providing a flexible prioritization method that can be applied as a basis for the fast screening of multiple assets.

## REFERENCES

[1] UNISDR, ‘Sendai Framework for Disaster Risk Reduction 2015–2030’, in *World Conference on Disaster Risk Reduction, 14 -18 March 2015, Sendai, Japan*, 2015. Accessed: Sep. 19, 2022. [Online]. Available: https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf

[2] X. Romão and C. Bertolin, ‘Risk protection for cultural heritage and historic centres: Current knowledge and further research needs’, *Int. J. Disaster Risk Reduct.*, vol. 67, p. 102652, Jan. 2022, doi: 10.1016/j.ijdrr.2021.102652.

[3] UNEP, ‘AGENDA 21. Technical report.’, in *United Nations Conference on Environment & Development, 3 to 14 June 1992*, Rio de Janerio , Brazil, 1992.

[4] UNISDR, ‘Hyogo Framework for Action 2005-2015 : Building the Resilience of Nations and Communities to Disasters’, in *World Conference on Disaster Reduction 18-22 January 2005*, Kobe, Hyogo, Japan, 2005.

[5] J. McGlade *et al.*, *Global assessment report on disaster risk reduction 2019*. UN Office for Disaster Risk Reduction, 2019. [Online]. Available: https://gar.undrr.org/sites/default/files/reports/2019-05/full_gar_report.pdf

[6] P. J. Ward *et al.*, ‘Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment’, *Nat Hazards Earth Syst Sci*, vol. 22, no. 4, pp. 1487–1497, Apr. 2022, doi: 10.5194/nhess-22-1487-2022.

[7] S. De Angeli, B. D. Malamud, L. Rossi, F. E. Taylor, E. Trasforini, and R. Rudari, ‘A multi-hazard framework for spatial-temporal impact analysis’, *Int. J. Disaster Risk Reduct.*, vol. 73, p. 102829, Apr. 2022, doi: 10.1016/j.ijdrr.2022.102829.

[8] M. C. de Ruiter, A. Couasnon, M. J. C. van den Homberg, J. E. Daniell, J. C. Gill, and P. J. Ward, ‘Why We Can No Longer Ignore Consecutive Disasters’, *Earths Future*, vol. 8, no. 3, p. e2019EF001425, 2020, doi: https://doi.org/10.1029/2019EF001425.

[9] C. E. Marrion, ‘More effectively addressing fire/disaster challenges to protect our cultural heritage’, *J. Cult. Herit.*, vol. 20, pp. 746–749, 2016.

[10] M. Papathoma-Köhle, M. Schlögl, and S. Fuchs, ‘Vulnerability indicators for natural hazards: an innovative selection and weighting approach’, *Sci. Rep.*, vol. 9, no. 1, Art. no. 1, Oct. 2019, doi: 10.1038/s41598-019-50257-2.

[11] M. S. Kappes, M. Papathoma-Köhle, and M. Keiler, ‘Assessing physical vulnerability for multi-hazards using an indicator-based methodology’, *Appl. Geogr.*, vol. 32, no. 2, pp. 577–590, Mar. 2012, doi: 10.1016/j.apgeog.2011.07.002.

[12] M. Papathoma, ‘Tsunami vulnerability assessment using a geographical information system with special reference to Greece’, PhD Thesis, Coventry University, 2003.

[13] R. Gentile *et al.*, ‘Scoring, selecting, and developing physical impact models for multi-hazard risk assessment’, *Int. J. Disaster Risk Reduct.*, vol. 82, p. 103365, Nov. 2022, doi: 10.1016/j.ijdrr.2022.103365.

[14] V. Silva, S. Brzev, C. Scawthorn, C. Yepes, J. Dabbeek, and H. Crowley, ‘A Building Classification System for Multi-hazard Risk Assessment’, *Int. J. Disaster Risk Sci.*, vol. 13, no. 2, pp. 161–177, Apr. 2022, doi: 10.1007/s13753-022-00400-x.

[15] T. M. Ferreira, R. Vicente, J. A. R. Mendes da Silva, H. Varum, and A. Costa, ‘Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal’, *Bull. Earthq. Eng.*, vol. 11, no. 5, pp. 1753–1773, Oct. 2013, doi: 10.1007/s10518-013-9447-2.

[16] D. Rapone, G. Brando, E. Spacone, and G. De Matteis, ‘Seismic vulnerability assessment of historic centers: description of a predictive method and application to the case study of scanno (Abruzzi, Italy)’, *Int. J. Archit. Herit.*, vol. 12, no. 7–8, pp. 1171–1195, Nov. 2018, doi: 10.1080/15583058.2018.1503373.

[17] P. Salzano, C. Casapulla, F. Ceroni, and A. Prota, ‘Seismic Vulnerability and Simplified Safety Assessments of Masonry Churches in the Ischia Island (Italy) after the 2017 Earthquake’, *Int. J. Archit. Herit.*, vol. 16, no. 1, pp. 136–162, Jan. 2022, doi: 10.1080/15583058.2020.1759732.

[18] S. Lagomarsino, ‘On the vulnerability assessment of monumental buildings’, *Bull. Earthq. Eng.*, vol. 4, no. 4, pp. 445–463, Nov. 2006, doi: 10.1007/s10518-006-9025-y.

[19] S. Lagomarsino and S. Podestà, ‘Seismic Vulnerability of Ancient Churches: II. Statistical Analysis of Surveyed Data and Methods for Risk Analysis’, *Earthq. Spectra*, vol. 20, no. 2, pp. 395–412, May 2004, doi: 10.1193/1.1737736.

[20] F. Ceroni, C. Casapulla, E. Cescatti, V. Follador, A. Prota, and F. da Porto, ‘Damage assessment in single-nave churches and analysis of the most recurring mechanisms after the 2016–2017 central Italy earthquakes’, *Bull. Earthq. Eng.*, vol. 20, no. 15, pp. 8031–8059, Dec. 2022, doi: 10.1007/s10518-022-01507-8.

[21] S. Lagomarsino, S. Cattari, D. Ottonelli, and S. Giovinazzi, ‘Earthquake damage assessment of masonry churches: proposal for rapid and detailed forms and derivation of empirical vulnerability curves’, *Bull. Earthq. Eng.*, vol. 17, no. 6, pp. 3327–3364, Jun. 2019, doi: 10.1007/s10518-018-00542-8.

[22] A. Marotta, D. Liberatore, and L. Sorrentino, ‘Development of parametric seismic fragility curves for historical churches’, *Bull. Earthq. Eng.*, vol. 19, no. 13, pp. 5609–5641, Oct. 2021, doi: 10.1007/s10518-021-01174-1.

[23] R. Figueiredo, X. Romão, and E. Paupério, ‘Component-based flood vulnerability modelling for cultural heritage buildings’, *Int. J. Disaster Risk Reduct.*, vol. 61, p. 102323, Jul. 2021, doi: 10.1016/j.ijdrr.2021.102323.

[24] D. D’Ayala *et al.*, ‘Flood vulnerability and risk assessment of urban traditional buildings in a heritage district of Kuala Lumpur, Malaysia’, *Nat. Hazards Earth Syst. Sci.*, vol. 20, no. 8, pp. 2221–2241, Aug. 2020, doi: 10.5194/nhess-20-2221-2020.

[25] S. Kincaid, ‘Fire prevention in historic buildings – approaches for safe practice’, *Hist. Environ. Policy Pract.*, vol. 13, no. 3, pp. 361–380, Jul. 2022, doi: 10.1080/17567505.2022.2098633.

[26] L. G. F. Salazar, X. Romão, and E. Paupério, ‘Review of vulnerability indicators for fire risk assessment in cultural heritage’, *Int. J. Disaster Risk Reduct.*, vol. 60, p. 102286, Jun. 2021, doi: 10.1016/j.ijdrr.2021.102286.

[27] N. Chettri, G. Dhaurali, T. Neopaney, T. Cheki, and D. Gautam, ‘Wind vulnerability and strengthening of Bhutanese vernacular roofs’, *Geomat. Nat. Hazards Risk*, vol. 13, no. 1, pp. 1511–1534, Dec. 2022, doi: 10.1080/19475705.2022.2086830.

[28] G. Sevieri *et al.*, ‘A multi-hazard risk prioritisation framework for cultural heritage assets’, *Nat. Hazards Earth Syst. Sci.*, vol. 20, no. 5, pp. 1391–1414, May 2020, doi: 10.5194/nhess-20-1391-2020.

[29] P. B. Julià and T. M. Ferreira, ‘From single- to multi-hazard vulnerability and risk in Historic Urban Areas: a literature review’, *Nat. Hazards*, vol. 108, no. 1, pp. 93–128, Aug. 2021, doi: 10.1007/s11069-021-04734-5.

[30] V. Despotaki, V. Silva, S. Lagomarsino, I. Pavlova, and J. Torres, ‘Evaluation of Seismic Risk on UNESCO Cultural Heritage sites in Europe’, *Int. J. Archit. Herit.*, vol. 12, no. 7–8, pp. 1231–1244, Nov. 2018, doi: 10.1080/15583058.2018.1503374.

[31] X. Romão, E. Paupério, and N. Pereira, ‘Metodologia para avaliação expedita do risco sísmico em bens culturais imóveis’, Instituto da Construção, Faculdade de Engenharia da Universidade do Porto, 2015.

[32] S. Cattari, S. Degli Abbati, D. Ferretti, S. Lagomarsino, D. Ottonelli, and A. Tralli, ‘Damage assessment of fortresses after the 2012 Emilia earthquake (Italy)’, *Bull. Earthq. Eng.*, vol. 12, no. 5, pp. 2333–2365, Oct. 2014, doi: 10.1007/s10518-013-9520-x.

[33] S. Degli Abbati *et al.*, ‘Seismic assessment of interacting structural units in complex historic masonry constructions by nonlinear static analyses’, *Comput. Struct.*, vol. 213, pp. 51–71, Mar. 2019, doi: 10.1016/j.compstruc.2018.12.001.

[34] R. Figueiredo, X. Romão, and E. Paupério, ‘Flood risk assessment of cultural heritage at large spatial scales: Framework and application to mainland Portugal’, *J. Cult. Herit.*, vol. 43, pp. 163–174, May 2020, doi: 10.1016/j.culher.2019.11.007.

[35] S. Ferrari, S. Oliveira, G. Pautasso, and J. L. Zêzere, ‘Territorial Resilience and Flood Vulnerability. Case Studies at Urban Scale in Torino (Italy) and Porto/Vila Nova de Gaia (Portugal)’, in *Urban Resilience for Risk and Adaptation Governance: Theory and Practice*, G. Brunetta, O. Caldarice, N. Tollin, M. Rosas-Casals, and J. Morató, Eds. Cham: Springer International Publishing, 2019, pp. 147–174. doi: 10.1007/978-3-319-76944-8_10.

[36] W. Weber de Melo *et al.*, ‘Flood Risk Assessment at the Douro River Estuary’, in *Climate Change and Water Security*, Singapore, 2022, pp. 37–49. doi: 10.1007/978-981-16-5501-2_4.

[37] M. Santos, M. Fragoso, and J. A. Santos, ‘Damaging flood severity assessment in Northern Portugal over more than 150 years (1865–2016)’, *Nat. Hazards*, vol. 91, no. 3, pp. 983–1002, Apr. 2018, doi: 10.1007/s11069-017-3166-y.

[38] Centro Funzionale Regionale Regione Marche, ‘Rapporto di Evento preliminare Maltempo 15, 16 e 17 settembre 2022 (in italian)’. Accessed: Mar. 01, 2023. [Online]. Available: https://www.regione.marche.it/portals/0/Protezione_Civile/Manuali%20e%20Studi/Rapporto_Evento_preliminare_20220915.pdf