COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-–14 June 2023

A BUILDING CLASSIFICATION SYSTEM FOR MULTI-HAZARD RISK ASSESSMENT OF HISTORICAL RELIGIOUS BUILDINGS

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Keywords: Disaster risk, Multi-hazard, Taxonomy, Vulnerability.

Abstract. *UnReinforced Masonry (URM) religious buildings have proven to require special attention in the context of natural hazards risk assessment due to their high vulnerability – connected to aging and types of construction — and to their strong links with communities from both an economic and historical – cultural perspective. However, the study of this building type is extraordinarily complex, especially when the analysis is conducted on a territorial scale and involves a large number of elements. In the Italian context, following the extensive damage caused by recent major earthquakes (e.g., L'Aquila 2009, Emilia 2012, and Central Italy 2016), damage detection survey forms for the post-emergency phase, both for ordinary and religious buildings, have been developed. Nevertheless, proper classification of URM religious buildings considering attributes related to vulnerability to non-seismic hazards, and worthwhile as a tool of prevention rather than damage relief, is still lacking. This paper focuses on the development of a new structural classification system for URM religious buildings based on the identification and categorization of a set of attributes related to vulnerability to landslides, earthquakes, and geological hazards (e.g., type of load-bearing wall, building height, soil type, etc.). The classification system is then validated on an initial portfolio of thirty-eight samples, located in a specific area of the Tuscany region (Italy), to classify religious buildings into distinct structural types.*

1 INTRODUCTION

Risk assessment procedures are usually based on the characterization of the hazards affecting the region of interest (in terms of expected frequency and intensity), the definition of the vulnerability of the assets exposed to the hazards, and the assessment of the assets' exposure. In a large-scale assessment, developing a model for each building identified is hardly feasible, as well as economically prohibitive. The need, therefore, arises to identify a methodology to classify buildings into typologies according to a given set of relevant attributes, which may effectively serve as seismic vulnerability attributes. The practice of categorising buildings based on building type, i.e., of defining a proper building taxonomy, has found increasing use in recent years to describe the seismic performance of existing structures. For example, in the United States, ATC-13 [1], FEMA 154 [2], and HAZUS [3] provide a building classification system based on local design and construction practices. Building taxonomies have also been developed In Europe over the years. The European Macroseismic Scale (EMS-98) [4], the RISK-EU project [5], and the Syner-G taxonomy [6], [7], are examples of classification systems developed for European buildings. Even on a global scale, attempts have been made to codify the built heritage. The Earthquake Engineering Research Institute (EERI) and the International Association for Earthquake Engineering (IAEE) have taken a big step forward in understanding and summarizing worldwide construction types in a unique building inventory, the World Housing Encyclopedia (WHE) project [8], [9]. Moving from the international to the Italian national context, the first-level AeDES form for post-earthquake damage assessment, the AeDES form [10], exploits buildings division into constructional typology to expeditiously survey the damage and usability of residential buildings, in the post-earthquake emergency phase. Another extremely valuable system for cataloguing buildings of historical and architectural interest is the ICCD standard for architectural heritage (Istituto Centrale per il Catalogo e la Documentazione). The Institute's purpose is to document and catalogue the archaeological, architectural-landscape, historical-artistic, and ethno-anthropological Italian cultural heritage. Although not directly related to the assessment of hazard vulnerability, this classification system is one of the few that accounts for the distinctive features of historical religious buildings. Indeed, despite the usefulness of all available classification systems, their thorough study has revealed inadequacy when it comes to historical religious buildings. Most of the existing taxonomies are limited to a list of ordinary building classes, and therefore lack adequate flexibility to characterize religious buildings. This type of building often requires a more in-depth analysis aimed at acquiring knowledge regarding the historical-constructive attributes (typological and dimensional data, analysis of the masonry, state of conservation, etc.), the study of macro-elements, and collapse mechanisms among others. As evidence of this, to classify earthquake damage, the Italian Civil Protection established an ad-hoc seismic detection survey form for monumental buildings and buildings of historical interest [11] (models A-DC for churches and B-DP for buildings, cf.DPCM 23-2-2006, G.U. n°55 of 7-3-2006). Furthermore, existing taxonomies usually refer solely to seismic risk, and very few of them account for multiple natural hazards [12]. Conversely, based on the multi-hazard risk assessment, great attention should be paid to combining building vulnerability-related information for each of the hazards considered.

Based on past efforts, the paper proposes a novel simplified classification system, developed specifically for masonry religious buildings. Through this new classification system, predominant building typologies, within the Tuscany region (Italy), are identified. This study is part of a broader research work whose objective is to develop a multi-hazard, spatial-oriented approach for the analysis of existing religious buildings. The approach proposed a quantitative risk analysis framework, performed on a territorial scale, where the consequence of the identified hazards on a set of religious buildings can be estimated as the product of the hazard's probability of occurrence, building typologies vulnerability, and exposure. In this context, vulnerability is obtained by performing sensitivity analysis on each identified typology to assess which attributes have a greater impact, with respect to the structural performance towards the identified sources of risk. Whereas the exposure is estimated considering both the artistic value of elements at risk and the rate of occurrence with which the religious buildings are used. Indeed, for effective prevention, a territorial scale risk analysis is of the utmost importance for taking rational decisions on how to mitigate the effect of potentially disastrous natural events and for planning adequate maintenance operations, as well as monitoring measures. Section 2 presents the methodology and objectives of the work in its entirety; Section 3 illustrated the outcome of data collection regarding the main hazards affecting the area of interest; Section 4 presents the criteria for the selection of case studies and on-site Rapid Visual Form; Section 5 illustrates and comments the results of the on-site surveys.

2 METHODOLOGY AND OBJECTIVES

The aim of the broader research, of which the work presented here is the initial phase, is to develop and apply a multi-hazard, spatial-oriented approach for the analysis of the existing masonry churches in a selected area of the Tuscany region, with the purpose of reaching beyond a sectorial, and therefore limited, notion of risks. With reference to the risk assessment process provided by the [13], the following main phases of the work may be identified:

1. **Context definition** - at the initial stage, external and internal context are considered. In terms of the internal context, the aim of the research is delineate as the determination of the risk potential of a sample of religious buildings located into a limited geographical area. As previously stated, the risk potential is quantitative estimated as the product of the hazard's probability of occurrence, building typologies vulnerability, and building's exposure. Crucial to this phase is the correct definition of risk criteria or damage threshold. As regard the definition of the external context, cultural, historical, and geographical factors of the area of interest are carefully studied;

2. **Risk identification** - in this phase the main hazards that are expected to affect the churches are identified, together with the factors most likely to influence risk assessment (e.g. the limitation of knowledge, the impossibility of performing invasive tests, the need to carry out expeditious on-site survey, etc.). This phase resulted in the definition of the main attributes to be accounted for in the categorisation of recurrent structural typologies and to the consequently definition of a Rapid Visual Survey form (hereinafter called RVS form) specifically designed to allow expeditious, non-invasive on-site surveying;

3. **Risk analysis** - the purpose of this phase is to assess the level of risk of the churches investigated. A Bayesian approach is used to describe the occurrence probability of hazards involved, whereas the churches exposure is established in correlation with significance (i.e., main or secondary parish church) and artistic value (e.g., presence of artefacts of historical-artistic interest). For what concern the vulnerability assessment, parametric numerical models are developed for each typology identified. In order understand the relevance of selected attributes on the structure vulnerability, sensitivity analysis are performed by varying both external actions (e.g., ground motion) and internal parameters (e.g., geometry in plan and elevation);

4. **Risk evaluation** - as the final phase, the analysis outputs are compared with the risk criteria in order to match each building with a Class of Risk, allowing for straightaway identification of buildings requiring more attention, facilitating the understanding of whether and how additional action is required;

5. **GIS model** - the development of a GIS spatial model that integrates all the data collected and elaborated (risk class, hazards, churches typologies, etc.). The purpose is to create a tool which is able to quickly visualise, through Risk Classes, buildings that most require intervention or that, depending on their position/type/etc. require to be closely monitored.

This article is going to discuss in detail only the external context definition, risk identification, and RVS form structure and first application. Other phases and subsequent developments will be dealt with separately.

3 CONTEXT DEFINITION AND RISK IDENTIFICATION

The area selected for the present study is located in the Northern part of the Tuscany region (Italy), more specifically within the Lucca district and ranging from the Lunigiana-Garfagnana area, which covers a part of the Northern Apennines, to the River Serchio middle valley. It is a hilly and mountainous area, characterized by major centres and industrial areas connected by the main road network, and small settlements reached by the secondary road network. Earthquakes and slope instabilities can be considered the two main hazards of the selected area. From the seismic point of view, the Lunigiana-Garfagnana area is characterised by earthquakes average magnitude Mw of 5.0 [14]; the 1920 earthquake, with a magnitude Mw=6.5, which caused extensive damage throughout the upper part of the Serchio Valley represents a significant exception. The area has proven to be also prone to slope instability phenomena, due to both the geological and geomorphological characteristics, and climatic characteristics of the Serchio basin [15]. In addition to the National seismic zonation [16], and slope instability inventories available at the regional level [17], the study also involved the collection and analysis of existing seismic micro-zonation studies, which provide useful information regarding the patterns of ground motion amplification, liquefaction, surface fault ruptures, and earthquake-induced slope instability.

Following the identification of the main hazards to which the area is subjected, the churches to be investigated were selected. The Garfagnana area and Middle Serchio Valley are endowed with a large number of Romanesque churches, mostly dating back to Roman times. Together with monasteries and hospitals, these served as shelter and support for travellers who passed through these places both for necessity and for pilgrimage. In fact, the *Via Francigena*, a route from Canterbury to Rome which was one of the most important European communication routes in medieval times, together with other religious and commercial routes, such as the ancient transfer routes that the shepherds and their flocks took seasonally, still winds through these localities. An accurate list of all the religious buildings located in the area was available thank to previous research conducted in the same area [18] and include approximately four hundred religious building (Figure 1a). Considering both the characteristics of the site and the location of the churches, a first set of samples was selected by superimposing the National seismic hazard map and the inventory of Tuscan landslide phenomena to the map of the listed historical religious buildings, by means of the QGIS software. The selected buildings resulted in approximately half of the total number of churches analysed, but were instrumental in the preliminary calibration of the developed RVS form. All selected buildings present unreinforced masonry structures and are referable to the Romanesque architectural style (Figure 1b). During the sample selection, preference was awarded to churches not plastered, so that the wall texture was visible, not excessively damaged or completely abandoned, to be able to access safely. Finally, churches part of monasteries or other religious complexes were avoided, as well as those incorporated in the urban aggregate, as it would become impossible to assess their vulnerability regardless of the context.

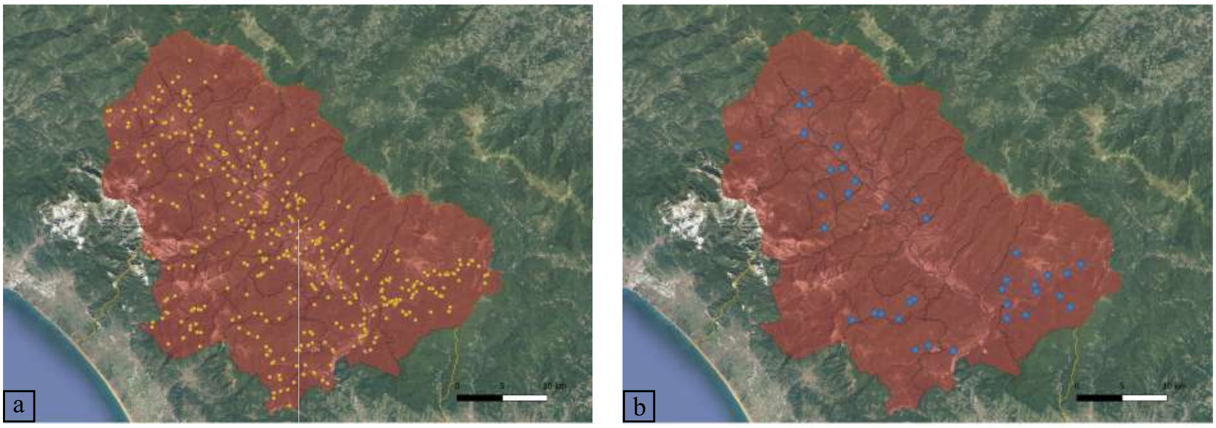

Figure 1: a) Identification of churches located in the selected area; b) Set of churches identified as samples.

4 BUILDING TYPOLOGY CLASSIFICATION

As previously mentioned, a review of existing literature and classification system was carried out initially. Although the authors were unable to evaluate all existing systems, this first step was crucial in understanding which attributes are recurrent in the various taxonomies [19–22], which are more relevant in defining the vulnerability to the various hazards [23–27], and how data are typically collected at the territorial scale in the context of the project [28–32]. The following section identifies building attributes adopted for the classification of historical-religious buildings into building typologies, focusing particularly on those attributes relevant in defining the vulnerability to earthquakes and slope movements, since, as mentioned, these hazards have been responsible for most of the economic and human losses in the area of interest. In this phase, the identified parameters are not ranked in terms of their influence on the structural response to the mentioned hazards.

4.1 Definition of the main attributes

The novel building classification was developed to identify predominant building classes among religious buildings. The chosen attributes must be compatible with a fast screening of a considerable number of churches and as mentioned, meaningful for the foreseen multi-hazard vulnerability assessment. In detail, the building taxonomy developed includes three main sections and nine sub-sections used to describe the material of construction, the lateral load-resisting system, the roof type, and the conservation state among other features. A more in-depth description of the attributes used is given in Table 1.

The three sections presented are reported on a Rapid Visual Survey Form which was used during the visual inspection of the selected churches. An example of a compiled RVS form is

Attribute	Description	Hazard addressed
General Data		
Survey data	day, month, year	hazard independent
Loci Information	province, municipality, sub-municipality (e.g., the Italian ”Provincia”, ”Comune”, and ”Frazione”)	hazard independent
Geographic Information	road type providing access to the building, position within the building context (e.g., isolated, attached to other buildings, at the corner of a block of buildings), GPS coordinates	relevant to both earthquakes and slope instabilities hazards
Building ID	type (e.g,. parish, cathedral etc.), name, diocese, occupancy rate (e.g. continuously, occasionally, no longer in use, etc.)	hazard independent
Vertical bearing structure	vertical and lateral load resisting system, construction material, quality and maintenance level	mainly relevant to earthquakes
Roof structure	roof shape, material, structural system, quality and maintenance level	mainly relevant to earthquakes
Internal ceiling	ceiling shape, material and structural system, quality and maintenance level	mainly relevant to earthquakes
Intervention	relevant interventions that various components of the church may have undergone (i.e., vaults reconstruction, re-covering, etc.)	relevant to both earthquakes and slope instabilities hazards
Building Layout		
	plan geometry and dimensions (i.e. one nave, three naves, Greek plan, etc.), ground floor level and height above grade, presence of valuable decorative elements, orientation of the building	relevant to both earthquakes and slope instabilities hazards
Facade Layout		
	facade type, quality and maintenance level, presence or absence of a bell tower, construction material of the exterior walls	mainly relevant to earthquakes

Table 1: Church attributes relevant for multi-hazard risk assessment.

presented in Figure 2.

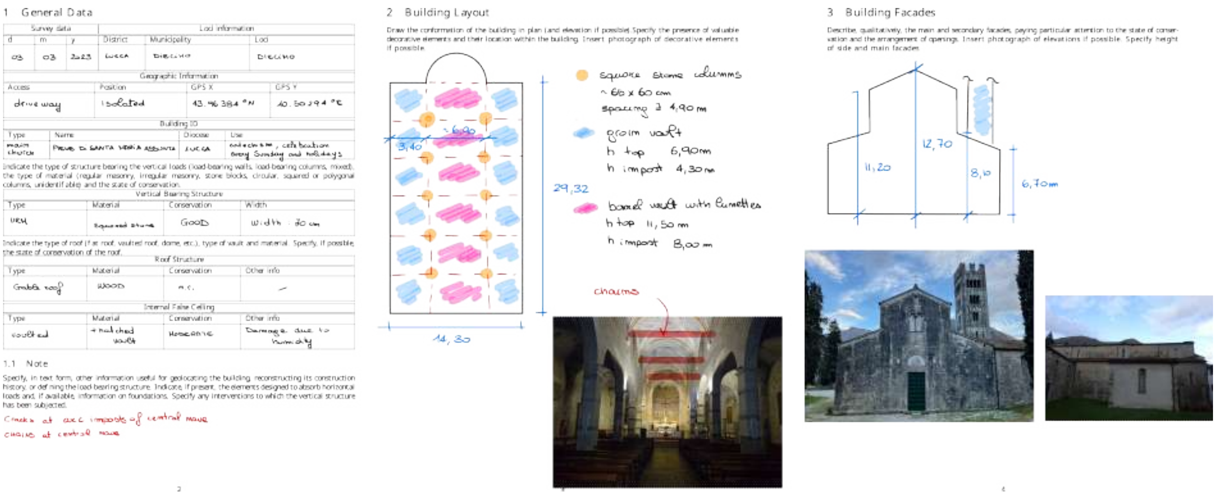

Figure 2: Example of RVS.

In comparison to more popular and well-known classification examples, the attributes chosen are fewer in number. However, this feature has proven to be valuable in the fast screening of a large number of buildings. To this purpose, the limited number of information gathered proved to be critical for categorizing buildings into major types.

4.2 On-site surveys

To validate the applicability of the proposed system, inspections were performed in the first thirty-eight churches selected as case studies. In addition to the compilation of RVS forms introduced above, the crack pattern of each church was observed and reported. No detailed maps were produced since the aim of the work is not to analyse extensively each church. In this framework, the damage surveys will be used as a means of the effectiveness of the result of the subsequent stages (vulnerability and risk analysis). Attention was also given to the surroundings of each building, to detect any possible evidence of ground movement, damage due to past earthquakes, or the presence of buildings that would interfere with the church itself. According to the plan layout, three recurring types of churches were identified during the first thirty-eight surveys (Figure 3): one-nave, three-nave, and Latin cross. Relevant variations in plan can be distinguished within these three types, owing primarily to the presence or lack of an apse and its shape, whether circular or rectangular. For the purpose of simplifying the subsequent stage of vulnerability analysis, however, the variations related to the apse are to be considered as variations within the same typology.

Other collected data show that the thickness of the load-bearing masonry ranges between 60 and 100 cm, while the height of the perimeter walls ranges between 6 and 10 m. The roof structure was always found to be made of wood. Where interior false ceiling was not present, wooden trusses were detected, in all others, it was not possible to identify through surveying alone whether the roof structure was pitched roofs or truss. The vaults that serve as the interior false ceiling are almost always barrel vaults with lunettes or cross vaults, either thatched or made of light material, usually local tuff. Only in two cases, related to more exposed churches, ribbed vaults were found and, in one case, a dome. In the case of three-nave churches, the

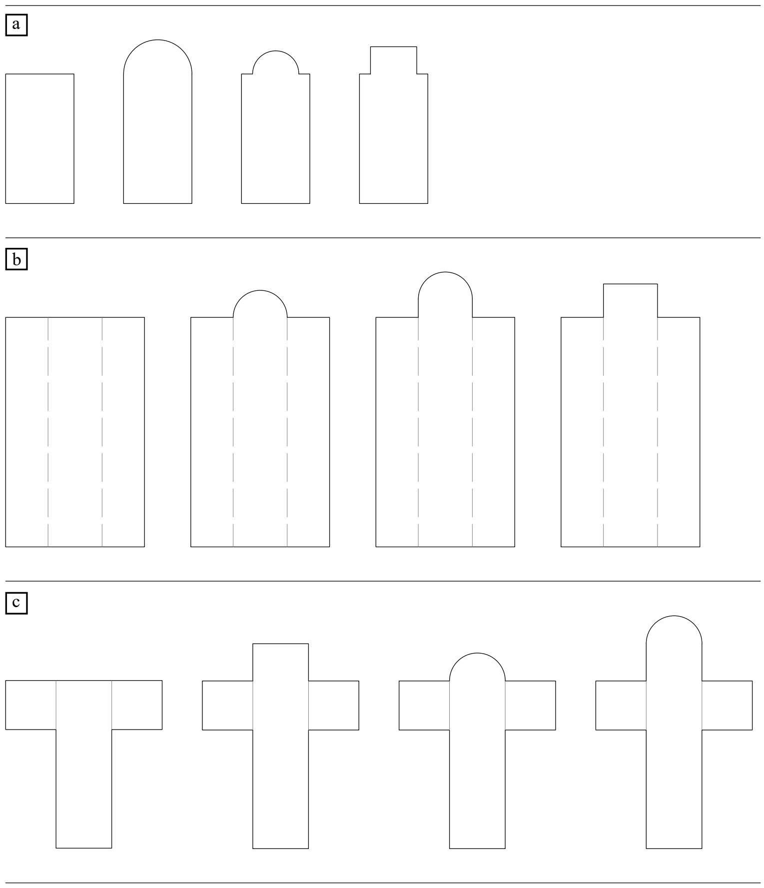

Figure 3: a) Type one: one-nave church; b) Type two: three-nave church; c) Type three: Latin cross

central and the secondary naves resulted to be separated by circular or squared columns, with spacing varying from 3 to 5 m. Moreover, as predictable considering the relevant seismicity of the area, all of the churches surveyed were found to have at least chains at the top of the central nave, in some cases also between the arches separating the main nave from the secondary ones. In some cases, surveyed churches are located on gently declining slopes, whose kinematisms are reflected by the crack pattern of the churches themselves and, if present, of the surrounding buildings.

5 CONCLUSIONS

Starting from existing taxonomies and vulnerability attributes, a simple structural classification system for the historical religious buildings was developed. The system was initially applied to a first sample of thirty-eight churches located in a selected area of the Tuscany Region in order to test its effectiveness within an expeditious screening project of a considerable number of historical religious buildings. The results obtained demonstrate that, despite being based on a limited number of attributes in comparison to more complex taxonomies, the proposed system effectively leads to the categorisation of buildings into three recurring main types: one-nave, three-nave, and Latin cross. This allowed the rapid visual screening of the entire portfolio of seventy-one churches and the progression to the next stage of vulnerability assessment.

6 ACKNOWLEDGMENTS

We are grateful to the graduating student Giacomo Bianchini for his support in data acquisition and survey.

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