Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 4085-409

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

SEISMIC RISK AND FUNCTIONAL ADAPTIVITY ASSESSMENT OF A HOSPITAL BUILDING BY RAPID VISULA SCREENING: A PILOT STUDY

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Abstract

Recent seismic events in Italy and COVID19 pandemic have underscored the importance of seismic safety and flexibility in public buildings, especially hospitals. These facilities should play a strategic role during disasters, as they are tasked with providing essential emergency aid to the population and ensuring the continuity of initial on-site healthcare interventions. Conversely, hospitals have often been found to be highly vulnerable to seismic actions and not adequately flexible in emergencies.
This study aims to develop a novel methodology to assess the resilience of Italian healthcare facilities by accounting for seismic performance and functional flexibility, with a focus on nonstructural elements and organizational aspects. The study implements a rapid visual screening (RVS) assessment based on the extension of existing methods, applied to a pilot hospital.
The methodology is based on an RVS-based estimation of seismic risk and flexibility indices, utilizing visual inspections, data collection, checklist completions, and question answering, and deriving quantitative estimations from elementary parameters to complex metrics. In par-

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12716.25419

ticular, the seismic risk index can be assessed as it is traditionally done, considering seismic hazard, vulnerability, and exposure, estimated by simplified methods defined in the literature. The definition of the flexibility assessment method is novel, and it is based on the combination of elementary flexibility indices, associated with nonstructural elements, and functionality and operational indices, depending on the hospital facility features. The preliminary methodology is applied with regard to the Sant'Anna e San Sebastiano hospital of Caserta (Italy), which is a national relevance hospital facility (AORN). The study finally provides the first tentative seismic risk and flexibility indices associated with the pilot hospital, but the methodology should be calibrated by more refined studies in the future.

Keywords: Resilience, Seismic risk, Functional adaptivity, Nonstructural elements, Rapid Visual Screening.

1 INTRODUCTION

For a community affected by a seismic event, the hospital, a large structure crowded with thousands of people with highly varied reactive capacities, is one of the most exposed and sensitive sites. However, it is also a vital organ, requiring quick and effective responses under stress conditions to mitigate the earthquake's damage. If the hospital can absorb the shock of the system and continue providing healthcare support, the community regains one of its cornerstones, on which its reaction and recovery can be based.

Investigations conducted following recent earthquakes, such as the 2016 Central Italy earthquake, have shown that the performance and functionality of healthcare structures after an earthquake are related not only to structural damage but also to damage to nonstructural elements and medical equipment [7]. Nonstructural elements can endanger people and the contents of a building during a seismic event and increase accidental losses during evacuation. The damage to nonstructural elements results in the greatest economic losses due to earthquakes; these can represent between 60% and 90% of the total cost of buildings with a usage class IV [8]. In addition to the costs caused by the damage to the elements themselves, their partial or total inability to be used can compromise the functionality of the building, even if the structure is safe, leading to further losses. Damage to nonstructural elements is more likely to occur from earthquakes or other natural hazards than structural damage; building regulations provide different hazard levels based on their likelihood [1].

2 HEALTHCARE FACILITIES AND RESILIENCE

Healthcare facilities may be subjected to various types of extreme events, ranging from natural disasters to human-made events. The impact of these events can vary from small-scale mass incidents to catastrophic numbers of injuries and fatalities [11].

In fact, the first wave of the COVID-19 pandemic revealed that most Italian healthcare facilities have poor flexibility, meaning they are unable to adapt to changes in functionality (e.g., converting regular wards into COVID wards) and show a low tendency to be isolated in case of an emergency.

The issue of flexibility in nonstructural elements and buildings, not only hospitals, is closely linked to the sustainability of constructions over their entire life cycle. With the current "Life Cycle Thinking" approach, much attention is being paid to the environmental, social, and economic impact of products in general, including buildings and building interventions. Flexible construction solutions that emphasize principles such as modularity, ease of disassembly, and reuse of elements are solutions that reduce the environmental and economic impact during the building's life cycle. Additionally, referring to the end-of-life phase of a building, it is easy to understand how functional adaptability reduces the impact of any change in usage.

Thus, in this modern perspective of sustainability throughout the life cycle of a building, where the designer must also consider performance parameters related to sustainability, the flexibility (or functional adaptability) of the building becomes a relevant performance parameter.

The availability of a procedure for evaluating the functional adaptability of buildings also represents an opportunity in the context of BIM (Building Information Modeling). In fact, having a tool that can provide a flexibility index for a building, starting from aggregated information in its digital twin, would be an additional benefit of digital tools for construction.

Functional adaptability is, therefore, an intrinsic requirement of a resilient system. Although the concept of resilience is widely used in other engineering contexts, it has not yet been well applied to nonstructural elements and healthcare facilities. In particular, the scientific literature lacks contributions on the topic of flexibility.

Today, also thanks to the introduction of the PNRR, the National Plan for Recovery and Resilience, one of the main objectives to be achieved in Italy is to transform hospitals into resilient structures. Resilience, understood as the ability of a system to respond and adapt to a relatively critical stress [15], has become an essential target parameter for healthcare facilities, both in relation to seismic issues and functional flexibility.

The primary goal of this work is to present an innovative approach for the development of a methodology for the rapid assessment of the resilience of healthcare facilities based on seismic risk measures of buildings and the flexibility of nonstructural elements. Since both seismic risk and flexibility are indicative factors of the resilience of a healthcare facility, a single resilience index has been introduced to encompass basic features that condition the resilience of hospitals.

3 METODOLOGY

3.1 Seismic risk

Seismic risk is defined as a function of three factors: seismic hazard, vulnerability, and exposure. The term "hazard" is used to express the probability that, in a given geographic area, an earthquake of a certain magnitude will occur within a specific time frame. The term "exposure" refers to the people, buildings, and generally all assets present in a specific geographic area that could potentially be destroyed or damaged as a result of an earthquake. Finally, the term "vulnerability" defines the susceptibility of a building or element to suffer damage when an earthquake occurs.

For a complete seismic risk assessment, in addition to the structural aspects, nonstructural elements and organizational aspects must also be considered [7]. The methodology developed in this work is based on previously published contributions in the literature, particularly the works of Perrone et al. [6, 7], Terrizzi et al. [2] and De Angelis and Pecce [1], who provided a fundamental theoretical and practical framework for the development of the approaches used in this study.

The new questionnaire for applying the RVS methodology to calculate the Seismic Risk Index, developed in this work, is largely based on the questions from the questionnaire by Perrone et al. [7] and additional questions derived from the vulnerability form developed by De Angelis and Pecce [1]. Thus, the new questionnaire consists of 20 questions related to the structural elements of the building; 62 questions related to nonstructural elements; and 27 questions concerning organizational aspects, for a total of 109 questions.

To identify seismic risk, a set of six vulnerability indices is used. Three indices are called primary and are evaluated using the three main sections of the proposed form (structural elements, I_{STR}; nonstructural elements, I_{NSTR}; organizational aspects, I_{ORG}). The other three indices combine the results of the primary indices with Seismic Hazard (HAZ) and Exposure (EXP), assigning different weights to each result. Each question on the vulnerability form is assigned an importance level (L_I), which can be low (L), medium (M), or high (H), corresponding to values of 1, 2, or 3, respectively. Each question is answered by selecting an expected level of vulnerability (L_V), which can be low (L), medium (M), or high (H), also associated with values of 1, 2, or 3, respectively. After assigning the importance and vulnerability levels, the unit indices and the maximum unit indices for seismic vulnerability are derived. By comparing the respective sums of these parameters, the three primary vulnerability indices (I_{STR}, I_{NSTR}, and I_{ORG}) are calculated. From the primary structural index (I_{STR}) and nonstructural index (I_{NSTR}), the Functionality Index (FUNC) is derived. In the formula used by Perrone et al. [7] to obtain functionality, some anomalies were found: if the structural index is high enough while the nonstructural index and the index related to organizational aspects are low, this formula could yield a low seismic risk, which is somewhat unusual. Moreover, the seismic risk values for a structural index of 0.67 and slightly larger values could vary by as much as 40%, which should not happen. Therefore, a new formulation (1) was proposed to avoid such issues.

$$FUNC = (1 - 0{,}4 \cdot I_{NSTR}) \cdot (1 - I_{STR}) \tag{1}$$

The vulnerability index (VULN) is obtained from a combination of the primary index related to organizational aspects (I_{ORG}) and the functionality index (FUNC). The formula for calculating vulnerability has also been modified compared to the one proposed by Perrone et al. [7], with the relationship (2), in order to avoid a jump in vulnerability values when the functionality is zero.

$$\text{VULN} = \begin{cases} [0{,}8 - (0{,}8 \cdot FUNC - 0{,}2 \cdot I_{ORG})] & se\ FUNC \geq 0{,}33 \\ 1 - \left(\frac{0.46 - 0{,}20 \cdot I_{ORG}}{0{,}33}\right) \cdot FUNC & se\ FUNC < 0{,}33 \end{cases} \tag{2}$$

Evaluating seismic hazard based on the reference seismic zone is certainly straightforward in a simplified methodology like the one proposed by Perrone et al. [7], but it can be improved or refined:

- The first limitation addressed concerns the maximum horizontal site acceleration values (ag), which are based exclusively on a return period (T_R) of 475 years. In the new formulation, a range of ag values has been considered, including any value of nominal life (V_N) and the usage coefficient (C_U), at the discretion of the designer.
- The issue of stepwise distribution of the hazard score has been overcome by considering a linear law instead.
- To address the excessive weight given to hazard in the final index evaluation, a score between 1 and 1,67 has been assigned to Hazard (HAZ).
- The new formulation takes into account not only the type of subsoil (S_S) but also the topographic category (S_T) through the coefficient S defined by the NTC-2018.
- Figure 1 shows the graphical representation of the new law for calculating seismic hazard (HAZ).

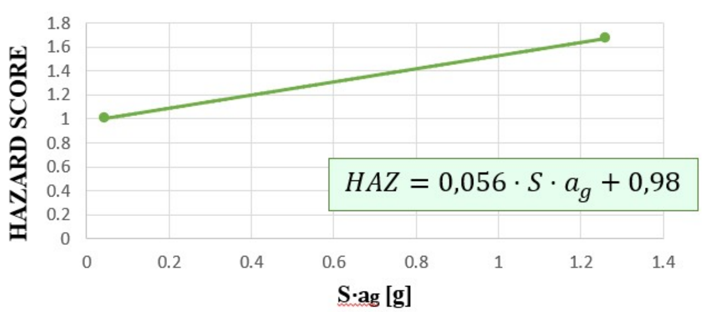

Figure 1: Graphical representation of Seismic Hazard as a function of S· a_g.

The Exposure Index (EXP) defines three exposure classes in terms of the importance and the population that benefits from hospital services. Thus, by combining the Vulnerability Index (VULN), the Exposure Index (EXP), and the Seismic Hazard Index (HAZ), it is possible to calculate the Seismic Risk Index (I_{RS}) using the relationship provided by Perrone et al. [7]. If the value of the Seismic Risk is below 0,33, the building is considered to have a "low" seismic risk; if it is between 0,33 and 0,67, the seismic risk is "medium"; otherwise, the seismic risk is "high."

3.2 Functional adaptivity

The second part of this work focuses on the functional adaptability of healthcare facilities, which are still under development. Functional adaptability is an essential characteristic of a resilient hospital and a key principle of the new "Life Cycle Thinking" approach in the construction sector. In relation to this topic, this work presents an approach of Rapid Visual Screening (RVS) for assessing the functional adaptability of hospital buildings. This procedure is meant to be used quickly, utilizing limited financial resources and easily obtainable data (such as architectural and technical drawings and hospital department inventories), in order to swiftly identify intervention priorities for improving the functional adaptability of healthcare structures in the area.

The RVS procedure focuses on nonstructural elements, which play a key role in the functional adaptability of buildings, starting with individual hospital departments. For each department, it first determines a primary flexibility index for each of the three macro-categories of nonstructural elements: architectural elements, technical systems, and content.

Once the flexibility indices for each department of the building are obtained, those related to departments on the same floor are combined to obtain the floor flexibility index. Finally, the floor flexibility indices are combined to obtain the building flexibility index, which represents the final result of the RVS procedure under consideration.

3.3 Resilience

Seismic resilience is the ability of a system to respond to and adapt to relatively critical stress and is a fundamental parameter for an hospital structure [13, 15]. Since both flexibility and seismic risk are indicative factors of a healthcare facility's resilience, it has been proposed to introduce a single resilience index that encompasses various aspects and reflects the actual resilience of the structure. To calculate this index, the seismic risk index and the flexibility index should first be assessed, and then these indices are combined to determine the resilience index. In this preliminary work, since it is highly innovative and the existing literature has not yet addressed this issue, only the flexibility and seismic risk indices are considered. Therefore, these indices need to be integrated with other aspects that may affect resilience.

This methodology, which is still in its early stages, is highly innovative. It is the first time that seismic risk and flexibility are systematically and combinatorially addressed to determine resilience, so further studies are needed for complete definition. Future work will improve the methodology by integrating any significant parameters that have not yet been addressed.

4 CASE STUDY FACILITY: CASERTA HOSPITAL

The Rapid Visual Screening procedure for calculating the flexibility index of healthcare structures, developed in this work and described in the previous chapter, was applied to a part (added section) of building F of the National and High Specialization Hospital Company (AORN) "Sant'Anna e San Sebastiano" in Caserta.

The necessary information for this application was gathered from data collected at the aforementioned hospital center. This data consists of architectural and system design draings, content survey forms, and multimedia files of nonstructural elements present in the areas under examination.

The use of this data will allow a preliminary application of the developed procedure, aimed at evaluating its ease of use, the reasonableness of the results, critical issues, and possible improvements. However, it is emphasized that a subsequent application, considering the same case study, could take place following a new data collection, carried out according to the RVS procedure itself, meaning with a data collection specifically oriented toward its application. Additionally, it is appropriate that the effectiveness of the procedure be tested through applications to case studies different from the one considered here.

The following figure represents the entire extent of the AORN "Sant'Anna e San Sebastiano" headquarters, consisting of a complex of twelve buildings. The building of interest for the application described in this chapter is, as mentioned above, building F; specifically, for the application of the RVS procedure related to flexibility, the added section of this building was considered.

Figure 5: Map of the AORN 'Sant'Anna e San Sebastiano' of Caserta (from the hospital's website).

Moving on to the description of the added section of building F (constructed between 1969 and 1970), made of reinforced concrete, it extends over four levels, in addition to the upper roof level: basement, ground floor, first floor, and second floor.

The areas on the basement level are designated for the hospital pharmacy and the neuroradiology department, which is further organized into a CT (Computed Tomography) area and an MRI (Magnetic Resonance Imaging) area. On the ground floor, there are: the front office for reception, the police office, and the interventional angioradiology department. The first floor is dedicated to the ophthalmology department, while the second floor is dedicated to the digestive endoscopy department. The roof of the building in question was also part of the data collection mentioned earlier, as it houses various support equipment for the functioning of medical devices and systems located on the internal floors of the building.

5 CONCLUSIONS

The aim of this work was to develop methodologies that would allow for a quick assessment of the seismic risk of a hospital building and the flexibility of the nonstructural elements that make it up, in order to identify a Resilience Index, essential for defining the ability of a healthcare structure to respond and adapt to a relatively critical stress.

For the calculation of seismic risk, a Rapid Visual Screening form was developed, following the forms already available in the literature. As is known, seismic risk takes into account seismic hazard, vulnerability, and exposure. For the calculation of vulnerability, this new form considers structural vulnerability, nonstructural vulnerability, and organizational vulnerability. Some modifications were made to the methodology of Perrone et al. [7] for the calculation of the functionality and vulnerability indices. Applying this methodology to building F of the hospital complex, it was found that the building is characterized by low vulnerability in terms of nonstructural elements and organizational aspects, and by medium vulnerability for the structural elements. Considering the exposure parameters and improving the method for calculating the seismic hazard index, the seismic risk of the entire building was ultimately determined to be "Medium."

In terms of flexibility, a flexibility evaluation form is currently under development, taking into account the weight, dimensions, presence or absence of wheels, and the degree of constraint of each nonstructural element.

The case study of the AORN "Sant'Anna e San Sebastiano" in Caserta was considered for developing the abovementioned methodology. The goal was to obtain an RVS methodology for assessing the functional adaptability of healthcare buildings that could be applied to the most general hospital structure case possible, as well as to verify its actual use in a short time with the input data listed above, which are easily retrievable. The study is ongoing and future activities will formalize and validate the functional adaptivity assessment methodology, as well as they will combine the results to the presented seismic risk assessment, in order to estimate a resilience index.

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