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RESILIENCE OF CONSTRUCTED ASSETS AGAINST NATURAL EXTREME EVENTS FROM THE ENGINEERING STANDPOINT

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Abstract

The safety of people and the high value of constructed assets and their contents, as well as their criticality in fulfilling the basic needs and the well-being of communities, have always prompted concerns regarding the built environment sustainability, resilience and reliability. The constructed assets' resilience is often linked with policymaking and strategies for the built environment in the aftermath of catastrophic or traumatic events. It is a multi-dimensional concept covering physical (e.g. quality of building design and construction), infrastructural (e.g. lifelines), environmental (e.g. natural hazards), economic-social (e.g. impacts on local communities), political-regulatory (e.g. building codes and standards) and organizational aspects (e.g. decision making strategies). Assuring the simultaneous fulfilment of these needs is key to the achievement of the Sustainable development Objectives (ODS). This is a challenge involving different stakeholders across all constructed assets life-cycle stages. This paper addresses the resilience of constructed assets against natural disasters from an engineering standpoint, namely with regards to building structural safety and serviceability. It presents risk-informed performance-based parameterization strategy and evaluation criteria to consider different levels of structural safety and serviceability in constructed assets against natural disasters.

1. INTRODUCTION

The resilience of buildings and civil engineering works has attracted the attention of several stakeholders, including engineering professionals from different fields, scientists, standardization bodies, investors and financial institutions, regulatory agencies, user groups of several, as well as administrative services at national and regional level. This interest stems from the broader view that resilience is a key issue for achieving the United Nations Sustainable Development Goals, in particular with regard to humanitarian issues and the need to provide the general public, including vulnerable groups, with a environment that can best adapt to future disaster risks [1]. Recent standardization efforts have led to an awareness of the need for a structured overview of information on the resilience of buildings and civil engineering works, particularly regarding the concept itself and the risks and measures of disasters. Regarding fundamental concepts, ISO 22845 classifies resilience in different contexts, as well as the definitions of resilience that are currently under development. For natural disaster risks, this international standard defines three types: i) induced by climate, ii) induced by earthquakes; and iii) induced by a human hand. The measures included in this document summarize the information relevant to the strategy and in the form of standards, guidelines, among others [2].

2. RESILIENCE AND NATURAL DISASTERS RISKS

Since resilience represents the ability of a building to resist, to absorb, to accommodate, to adapt, to transform and to recover from the effects of danger, it is necessary to understand the importance of disaster risks that are a pre -requirement for the development of resilience standardization for buildings and civil engineering works. There are different uses of the concept of "resilience" around four basic concepts: i) resilience as recovery from trauma and restoration of balance; ii) resilience as a synonym for robustness; iii) resilience as the opposite of fragility, that is, as graceful extensibility when surprise defies limits; and iv) resilience as network architectures that can support the ability to adapt to future surprises as conditions evolve. Two categories of natural disaster risks related to buildings and civil engineering works are mentioned: i) induced by climate; ii) induced by earthquakes. Considering that the useful life of buildings and civil engineering works is tens or even hundreds of years, it is also necessary to consider the future possibilities of risks and extreme natural events.

In line with what is defined in the ISO 22485 standard, the frequency and economic losses of global meteorological disasters are considered to have an obviously upward trend, being detrimental to the security of life and human property, as well as to sustainable economic and social development. Looking ahead to the coming decades of the 21st century, global climate risks will continue to increase due to climate change and the increased exposure and vulnerability brought by urbanization, high temperature, low temperature, heavy rainfall, tropical cyclones, drought, and rising sea levels. can have a certain impact on buildings and civil engineering works can have a certain impact on construction and civil engineering works. These impacts have important implications for considering the long-term pattern of resilience of buildings and civil engineering works. Some countries and organizations have proposed initiatives and action plans to address climate change, targeting parts of cities, communities, buildings, infrastructure, etc., which may have certain implications for the resilience of buildings and civil engineering works. Also, in alignment within ISO 22485, it appears that global seismic risk remains severe today. In fact, seismic actions are natural hazards with more catastrophic consequences for human beings. With rapid urbanization in recent years, a large percentage of the population as well as buildings is inevitably very exposed to seismic risk. Likewise, aging and changes in the stiffness and strength of buildings can also severely damage the safety and maintenance of existing engineering structures. It is challenging to identify requirements for resilience using traditional seismic resistance methods. In recent seismic actions, although some of the buildings have not collapsed, it turns out that they could hardly be repaired due to the severe damage identified, which inevitably causes huge economic losses and a significant social impact. The above questions indicate that improving resilience in structures and communities is essential.

The result of the literature review [ref várias] was that the resilience of assets built against natural risks can be structured in five dimensions: environmental, economic, organizational, social, and technical. These dimensions are aligned with: i) the essential pillars for economic, social and environmentally sustainable development defined by the UN in EC0-92 Agenda XXI (United Nations Conference on Environment and Development); ii) the four technical, organizational, social and economic dimensions [3]; and iii) the dimensions mentioned in several other selected documents (ranging from 3 to 10 dimensions), considering that different terminologies were used to describe the same characteristic and the need to avoid overlapping concepts.

3. STRATEGY AND CONTRAMEASURES

Currently, practice and research related to building resilience strategies and civil engineering works have progressed to some extent. In different ways, several strategies are relatively consolidated in standards and guidelines; some are implemented in certain cases; and some are still in the development stage. For different types of disaster risks, different systems are broad-spectrum, targeting various types of disaster risks, while others focus on a single type. Thinking about the future and its security, some climate-related strategies consider the impact of climate change on buildings and civil engineering works. Measuring the resilience of buildings and civil engineering works has advanced to some extent. The characteristics of the data collected are like those of the strategies. Some of them are relatively consolidated and standards, classification tools, etc. have been created, and others are still under development. Some are for several types of disaster risks, while others are for a single type. As the limits between strategies and resilience measures are sometimes unclear, the respective resources collected can contain both types of information. Table 1 summarizes typical resilience measures according to the disaster category of extreme natural events according to ISO 22845.

Table 1. Typical features for resilience measurements

Features	Riscos/Ações	
	Climate	Seismic
USRC Building Rating System	X	X
B-READY	X	X
FORTIFIED Commercial	X	
The Resilient City		X
Seismic Performance Assessment of Buildings		X
Standard for Seismic Resilience Assessment of Buildings		X
REDi		X

4. RESILIENCE RATING MODEL

4.1. RATING SCALE

The proposed resilience rating model for buildings seeks to meet the ISO / TR 22845 standard focusing on natural disasters whose national exposure is high or medium, adapted from [4]: Earthquakes, floods (urban, river, sea), fires and tsunamis. The proposed model has a hierarchical structure with three layers: dimensions, indicators and parameters and follows the following principles: i) Minimize the reduction in performance; ii) Minimize the recovery time after an event and iii) Maximize the recovery capacity.

The proposed rating model is based on existing resilience rating systems [4,6-8] and sustainability rating systems [9-12] that are reasonably mature. A semi-quantitative classification method is adopted. In this way, it is possible to graduate progressive levels of performance for each indicator ensuring: i) accessible language, both in terms and in concepts, which allows understanding by individuals who work or are qualified in management of facilities and related built assets, ii) criteria applicable to buildings with different types of use and iii) identification of the level of attention required for the analysis of indicators and dimensions [5]. Following [9], the adopted observable scale meets the recommendations of ISO 11863 [11] as it considers 5 different levels expressed in single digit integers on a scale of 1,3,5,7 and 9, where 1 corresponds to the worst performance and 9 to the best. This scale allows even levels to be used when the correct assessment is between two levels (Table 2).

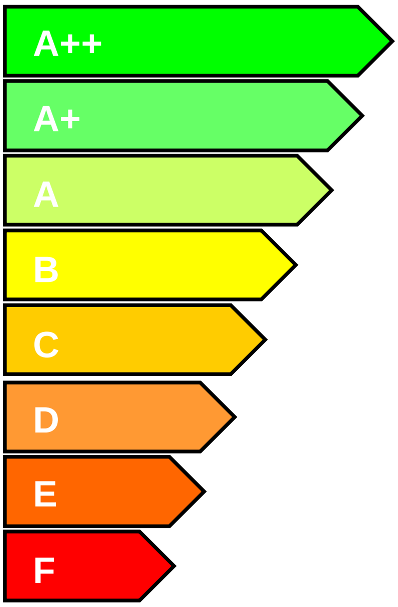
For the sake of simplicity, the weighting of each parameter in the pilot test proposal is considered of equal importance. This allows the identification of the overall performance of the building and the performance of individual aspects. For a clearer interpretation of the final score, the numerical score can be transposed into resilience classes from F to A ++ (Figure 1) allowing the differentiation of resilience levels to be easily understood and intuitive.

Table 2. Rating system

Score	Generic calibration
9	Exceptionally demanding
[7,9[	Clearly higher than normal, but not exceptionally demanding
[5,7[	Typical, medium or normal
[3,5[	Clearly lower than normal, but acceptable in some duly justified situations
[1,3[	Exceptionally less than normal, but acceptable in duly justified exceptional situations

Table 3. Proposed evaluation scale

Class	Average score
A++	[8,9]
A+	[7,8[
A	[6,7[
B	[5,6[
C	[4,5[
D	[3,4[
E	[2,3[
F	[1,2[



4.2. RATING METRICS

The definition of indicators and parameters aims to assess resilience and facilitate communication and consultation procedures. The parameters subdivide the indicators, and, in turn, each set of indicators expresses in more detail each of the dimensions mentioned above. Their selection was proven through a literature review, considering that: i) the selected parameters are possible to measure; ii) there is information available for its quantification and iii) it is desirable to avoid overlapping or repetition of metrics. An initial list of more than 200 indicators, divided by 5 dimensions (environmental, economic, organizational, social, technical) has been revised and reduced to 16 indicators, which have been subdivided into 75 parameters that best suit the purpose of the intended classification system. The main drivers of the review process were the elimination of repetition of indicators and those that express a perspective at the level of urban and community concerns, but which do not necessarly improve resilience at the level of built assets. The evaluation criteria defined for each parameter were initially established based on the thresholds of different metrics. It is expected that the review and calibration process of the indicators, parameters and evaluation criteria will be iterative. Following ISO 31000, this process must be monitored for the influence of judgments or opinions, lack of data and difficulty in quantifying [5].

The Environmental dimension (D1) includes 4 indicators (I1-Earthquake, I2 - Tsunami and tidal effect, I3 - Flood, I4 - Fire) and 25 parameters (P1- Seismic zoning - type 1 EC8; P2 - Seismic zoning - type 2 EC8,; P3 - Seismic vulnerability of the PDM soils; P4 - Slope of the terrain; P5 - Type of soil EC8; P6 - Distance to cliffs; P7 - Altitude of the terrain; P8 - Distance to the coast; P9 - Distance to the river; P10 - Natural barriers in the surroundings; P11 - Man-made barriers in the surroundings; P12 - Movable objects; P13 - Rows built between the coast and the building; P14 - Susceptibility to the direct tidal effect PDM; P15 - Relative location; P16 - Distance to the river ; P17 - Natural barriers in the surroundings; P18 - Man-made barriers in the surroundings; P19 - Vulnerability to floods PDM; P20 - Distance to vegetation; P21 - Density of vegetation; P22 - State of maintenance of vegetation; P23 - Type of vegetation; P24 - Adjacent buildings; P25 - Proximity to the industrial zone). This dimension seeks to foster a broad understanding of environmental issues, focusing on the area's vulnerability to natural disasters in the adapted upper and middle categories [4]. The parameters were calibrated for the case of Portugal, providing an overview of the potential threats as well as the determination of the intrinsic characteristics of the study area, such as altitude, distance to the sea and river, slope, etc., which increase the propensity to the determined risk. The assessment related to natural disasters must be carried out for the present and the future, considering that climate changes modify the frequency and intensity of disasters.

The Economic dimension includes 2 indicators (I1 - Insurance; I2 - Financial and strategic implications) and 3 parameters (P1 - Insurance against natural disasters; P2 - Financial plan; P3 - Economic assessment of downtime). Economic aspects are crucial to make a building resilient and can greatly affect the quality of the building, especially during and after suffering the impacts of a natural disaster [12]. Studies show that good economic management and consistent financial availability improve the response to natural disasters, and the recovery period is shortened. This dimension is related to the owner's monetary capacity in the face of imposed disturbances, including expenses with repairs, losses of assets and monetary losses with activities temporarily closed.

The Organizational dimension includes 2 indicators (I1 - Internal organization; I2 - External organization) and 10 parameters (P1 - Business continuity plan; P2 - Risk management analysis; P3 - Post-disaster recovery plan; P4 - Routine; P5 - Plans and post-disaster exercises; P6 - Learning and updating; P7 - Destructive event data; P8 - Responsible; P9 - Compliance with the existing regulatory scenario; P10 - External standards for resilient construction). The organizational capacity of buildings is related to the management capacity in emergency situations, that is, decision making by the owner in relation to the identification, monitoring and risk management. This dimension focuses on the pre-disaster, promoting preventive actions that reduce the impacts of natural disasters, guaranteeing a good performance of the building, minimizing the harmful consequences, and creating the minimum disturbance for the users [13]. Topics beyond the reach of the owner were also considered, such as compliance with the existing regulatory scenario and the use of other resilience standards. These indicators guarantee the safety of construction and contribute to the preparation of buildings in the face of existing obstacles, helping to identify and prioritize problems.

The Social dimension includes 2 indicators (I1 - Emergency infrastructures; I2 - Social Responsibility) and 7 parameters (P1 - Access to police stations; P2 - Access to fire stations; P3 - Access to emergency infrastructure; P4 - Access to hospitals and health centres; P5 - Occupants; P6 - Disclosure; P7 - Social vulnerability). The social dimension seeks to relate the building to society and the surrounding community, which are intrinsically related, especially in times of stress, whose individual response is difficult to identify and parameterize, but it is important to consider. Studies in resilient communities show that attentive and sensitive cities to individuals are better prepared for disasters, reducing their consequences, [14-15], the same can be said for buildings. For this reason, factors such as the social vulnerability of the building, which corresponds to the number of elderlies, children and disabled people were considered. In addition, the intention is to emphasize the role of citizens in responding to disasters and the proximity of the building to community infrastructure, such as firefighters, police stations, hospitals, etc.

The technical dimension includes 6 indicators (I1 - Conservation; I2 - Accessibility; I3 - Building seismic security; I4 - Building security against fire; I5 - Building security against flooding; I6 - Building security against tsunami) and 29 parameters (P46 - Year of construction; P47 - Structural system; P48 - Conservation status; P49 - Density of buildings; P50 - Alternative routes; P51 - Street characteristics; P52 - Plan irregularity; P53 - Height irregularity; P54 - Interaction with adjacent buildings; P55 - Slope difference; P56 - Expansion joint; P57 - Clearance between overlapping spans; P58 - Gas installations; P59 - Control and smoke evacuation systems; P60 - Intrinsic fighting means; P61 - Electrical installations; P62 - Fire compartment; P63 - Security team; P64 - Outdoor fire hydrants; P65 - Emergency lighting and signalling; P66 - Fire extinguishers; P67 - Fire detection and alarm; P68 - Escape routes; P69 - Barriers; P70 - Flood pumping systems; P71 - Exposure of the walls; P72 - Number of floors (flooding); P73 - Number of floors (tsunami); P74 - Orientation; P75 - Ground floor hydrodynamics). This dimension focuses on the technical and physical characteristics of the building and its surroundings, which are crucial to guarantee resistance to natural disasters and to minimize the damage caused by them [13]. This dimension derives from technical approaches and is related to the engineering component of a building, which includes structural, mechanical, electrical and hydraulic security and the assessment of the building's physical vulnerabilities in the face of the natural disasters identified above. The building's redundancy and robustness strategies are included in this dimension, such as improvements beyond the building code or installation of natural disaster protection systems [12]. Intrinsic characteristics of the construction such as age, number of floors, irregularities, quality of construction, current condition and state of conservation are considered in this dimension. The characteristics of the surroundings should also be analysed, especially because of its impact on post-disaster recovery [13] as the accessibility of the building that depends on several aspects, such as the existence of alternative routes, density of the building and characteristics of the streets.

5. CASE-STUDY

The principals of two school buildings in the same geographical area, both built in the 1950-60 period, will be taken, however one of them underwent a total rehabilitation in the decade of 2010. The main building of “3 - Escola 1” whose gross construction area are 10000m2, it is isolated, regular in height and plan, has 3 floors and 1 basement and in 2011 it underwent a deep rehabilitation to become a building in compliance with the current one in force at the time. The structure is made of resistant reinforced concrete walls based on micropyles and its state of conservation is high, they do not alter relevant damages. The main building of “4- Escola 2” is isolated and has 5000m2 of gross construction area, has 3 elevated floors, is regular in plan and height, its state of conservation is moderate. It was not possible to obtain information regarding the composition of the building.

These school buildings had extended interventions in the scope of a public investment program, between 2009 and 2011. The materials and constructive solutions to be adopted considered the current needs (regulatory and legislative requirements) as well as the maintenance system to be implemented. The interventions contemplate equipment, facilities and technical designs currently required in legislative environment, structural safety, seismic reinforcement, and fire safety aspects.

Concerning the resilience aspects, the performance of a building depends on its parts such as: Structure; Services and equipment; External elevations, roofs, and interior divisions; and Landscaping. To carry out an economic analysis, performance indicators related to the building’s intervention are defined for each part:

1. School building 1 (D. Leonor) costs: 27,38 €/m2 (structure); 87,29 €/m2 (services and equipment); 173,28 €/m2 (external elevations, roofs, and interior divisions); and 7,48 €/m2 (landscaping).

2. School building 2 (E. Santos) costs: 9,76 €/m2 (structure); 83,30 €/m2 (services and equipment); 189,16 €/m2 (external elevations, roofs, and interior divisions); and 8,14 €/m2 (landscaping).

In the following are presented the results obtained considering the resilience rating model proposed. Figure 1a (for school1) and Figure 1b (for school 2) comprise the results considering the five dimensions analysed, while Figure 3 (school 1) and Figure 4 (school 2) correspond to the results obtained for the main representative indicators considering the type of structure and the type of intervention performed.

Figure 1. Resilience rating for dimensions covered: a) school 1; b) school 2

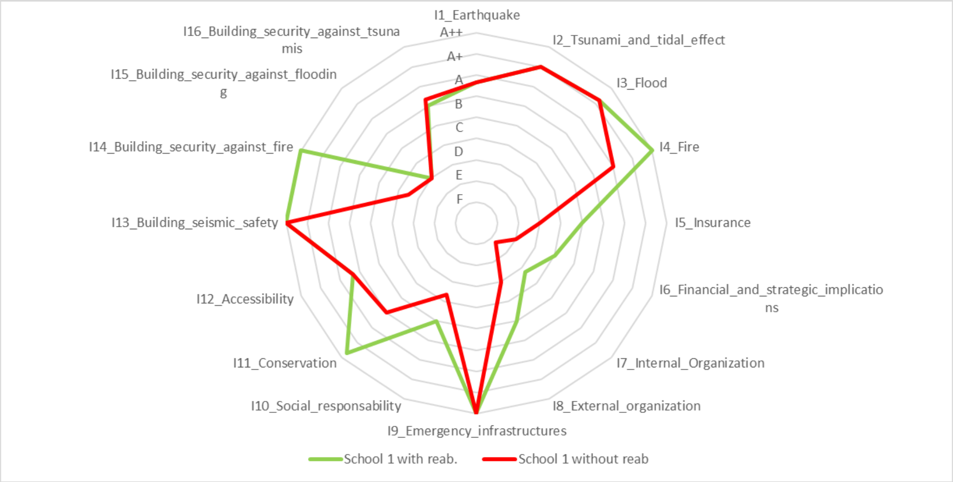


Figure 2. Resilience rating for school 1 considering the main representative indicators covered

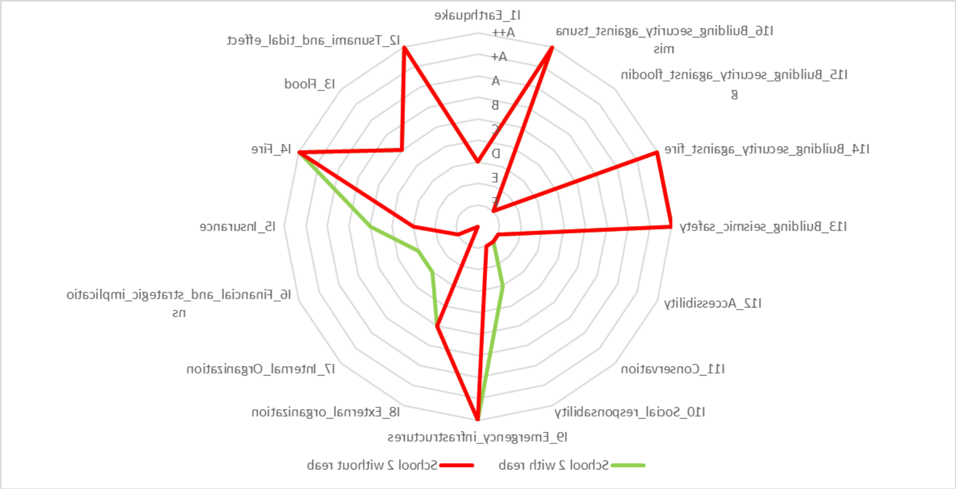


Figure 3. Resilience rating for school 2 considering the main representative indicators covered

In school buildings that are the object of analysis in the case study, there is a considerable discrepancy in the technical classification since one of the school buildings has undergone a more in-depth intervention. The different dimensions have similar classifications with slight differences in the social dimension because the school that was the object of a deeper intervention is a school more oriented towards older students (secondary education), and as such serving less children and elderly people who naturally appear less vulnerable users.

6. CONCLUSIONS

The work presented contributes to a discussion on ways to measure the resilience of built assets, namely based on a resilience classification system composed of 5 dimensions, 16 indicators and 75 parameters. The proposed classification system covers not only the building's intrinsic qualities, but also its interdependence with the community, surroundings, and users in the post-disaster context.

The proposed resilience classification system allows different stakeholders to identify which aspects efficiently and quickly should be improved in the built assets so that it is possible to establish investment priorities to increase their resilience in the face of extreme events. This information can be useful for all interested parties, that is, the owner, asset managers, insurance companies and municipal entities, allowing a better perception of the important contribution of the built assets to the construction of resilient communities.

Related to the economic indicators, it is noted that the rehabilitation interventions have a positive impact in the resilience score (according to the evaluation scale presented). The investment in the rehabilitation interventions is directly proportional to the increase of the resilience score.

However, it is still necessary to develop complementary work to implement the proposed assessment in number and diversity representative of the types of built assets, as well as to extend the scope of the proposed multivariate classification system with respect to other types of risks (for example, human-induced risks) and the identification of countermeasures and their classification.

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