sustainability

Article

Risk-Informed Performance-Based Metrics for Evaluating the Structural Safety and Serviceability of Constructed Assets against Natural Disasters

Nuno Marques de Almeida [1,*], Maria João Falcão Silva [2], Filipa Salvado [2], Hugo Rodrigues [3] and Damjan Maletič [4]

[1] Department of Civil Engineering, Architecture and Georesources, University of Lisbon (IST), 1049-001 Lisboa, Portugal
[2] Building Economy, Management and Technology Unit, Laboratório Nacional de Engenharia Civil (LNEC), 1700-066 Lisboa, Portugal; mjoaofalcao@lnec.pt (M.J.F.S.); asalvado@lnec.pt (F.S.)
[3] Civil Engineering Department, University of Aveiro, 3810-193 Aveiro, Portugal; hrodrigues@ua.pt
[4] Faculty of Organizational Sciences, University of Maribor, 4000 Kranj, Slovenia; damjan.maletic@um.si
* Correspondence: nunomarquesalmeida@tecnico.ulisboa.pt

Abstract: The tangible and intangible value derived from the built environment is of great importance. This raises concerns related to the resilience of constructed assets to both human-made and natural disasters. Consideration of these concerns is present in the countless decisions made by various stakeholders during the decades-long life cycle of this type of physical asset. This paper addresses these issues from the standpoint of the engineering aspects that must be managed to enhance the structural safety and serviceability of buildings against natural disasters. It presents risk-informed performance-based parameterization strategies and evaluation criteria as well as design methods to embed differentiated levels of structural safety and serviceability of buildings against wind, snow, earthquakes and other natural agents. The proposed approach enables designers to assure the resilience and reliability of building structures against natural risks.

Keywords: structural performance; engineering risk; buildings; wind; snow; earthquake

Citation: de Almeida, N.M.; Silva, M.J.F.; Salvado, F.; Rodrigues, H.; Maletič, D. Risk-Informed Performance-Based Metrics for Evaluating the Structural Safety and Serviceability of Constructed Assets against Natural Disasters. *Sustainability* **2021**, *13*, 5925. https://doi.org/10.3390/su13115925

Academic Editors: Dragan Komljenovic, Georges Abdul-Nour and François Gauthier

Received: 26 April 2021
Accepted: 21 May 2021
Published: 24 May 2021

1. Introduction

It is a challenge to ensure resilience and reliability concerns under the ever-increasing performance requirements of the multiple stakeholders involved in the life cycle of building projects [1,2]. In this context, large amounts of technical and non-technical information need to be appropriately managed and communicated [3]. However, technical information is generally less accessible by the generality of the stakeholders of building projects as compared to other less complex information dimensions, which are often emphasized by the building promoters. The performance concept is particularly suitable to communicate with the public or other stakeholders without an intimate understanding of the technical dimensions of building assets [4], but the latter must be embedded within the performance-based information delivered to the public [5].

The Architecture, Engineering, Construction and Operation (AECO) sector needs to adopt future-proof methodologies and provisions that anticipate future events and eventual changes in end-user needs, minimize negative impacts and maximize opportunities that lead to sustainable value creation throughout the life cycle of building projects. This can be achieved through the appropriate design and construction quality control and other building policies or regulatory elements, including those aimed at ensuring resilience to unexpected or uncontrollable events and circumstances, or the ability to maintain and/or assure the operations during/after an adverse event (e.g., climate change impacts, extreme weather events, seismic events). Building resilience is often linked with policymaking and strategies for the built environment in the aftermath of catastrophic or traumatic changes. It is a multidimensional 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) [6–11].

In the first decade of the 21st century, three major conceptual approaches in the building sector began to merge [12]: quality, performance, and risk. New applications derived from these three interrelated approaches reconcile and integrate conventional management philosophies and enable innovation in the building sector [1,13]. In this context, it is worth mentioning the efforts to organize risk-informed performance-based metrics for construction projects. In this regard, Figure 1 distinguishes two risk contexts (external and internal) that overlap with two complementary points of view: one centered on systems organized by humans (horizontal axis) and the other on organizations (vertical axis) [14]. It is worth noting that a given construction project can be considered as a specific type of organization.

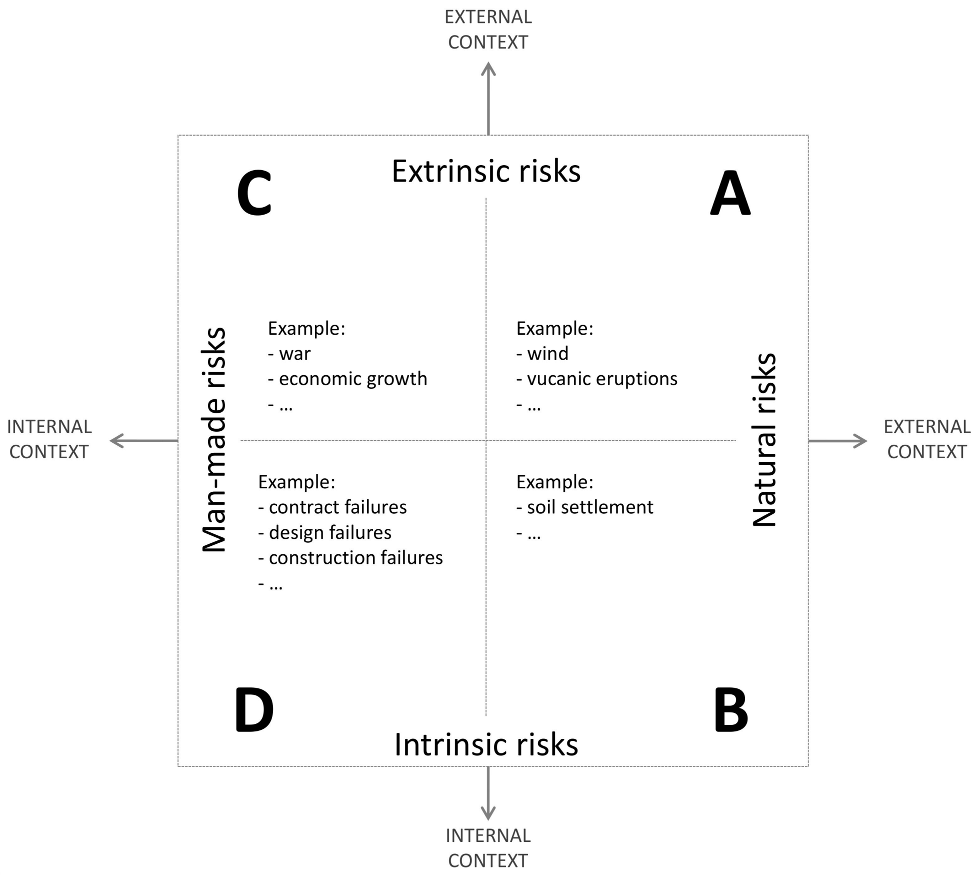

Figure 1. Risk modelling for construction projects [14].

From the standpoint of human-organized systems, two major groups of risks are commonly distinguished [15–17]: natural hazards (quadrants A and B in Figure 1) and human or human-made risks (quadrants C and D in Figure 1). Natural hazards are risks that occur outside of human-organized systems, such as climate-related risks (winds, floods, etc.) and geological risks (soil settlements, earthquakes, volcanic eruptions, etc.), among others. Risks that occur within human-organized systems include social risks (criminal acts, riots, etc.), political risks (wars, civil disorder, etc.), economic risks (inflation, unemployment, fluctuations in currency values, etc.), financial risks (changes in interest rates, cash flows, etc.), legal risks (changes in regulation or contractual aspects, aspects related to licensing and/or patents, etc.), health risks (epidemics, etc.), management risks (related to quality assurance, cost control, human resources, planning, etc.) and technological risks (design or operation failures, etc.), among others (for example, related to cultural and religious behaviors).

In cases where risk categorization uses a view centered on organizations (namely, the participants in a building project), the formulation of risk is usually based on the causes and potential consequences (cause-effect determination). In this case, authors tend to distinguish two main risk groups [17–22]: intrinsic risks (quadrants D and B in Figure 1) and extrinsic risks (quadrants C and A in Figure 1). Intrinsic risks are related to the internal resources of the organizations, i.e., those that are under the responsibility of those involved in the building project, including owners (delays in payments, stipulation of unrealistic deadlines, etc.), designers (design errors, delays in execution, etc.), builders and subcontractors (accidents, defects in the service provided, etc.) and suppliers (non-compliance with deadlines, etc.), among others (including those that can be associated with the end-users). Extrinsic risks are related to resources that are external to the organization and typically not under the responsibility of the main participants in a building project, such as political risks (strikes, changes in the law, corruption, delays in approvals, etc.), social and cultural risks (criminal acts, local protectionism, racial conflicts, etc.), economic risks (inflation, scarcity of basic resources, etc.) and natural risks (weather and other unforeseen events), among others.

This paper focuses on engineering risks informing performance metrics related to natural disasters induced by natural agents such as wind, water (e.g., snow, floods), or earthquakes (quadrant A). Risk-informed performance-based metrics related to, e.g., the condition of the soil (quadrant B), a situation of alteration of technical regulations (quadrant C) or the design and execution of the building (quadrant D) are excluded from the scope of this paper.

Section 2 of the paper presents the broad context of the research with regards to the pressing issues raised by increasing exposure of the built environment to natural disasters and the need to enhance its resilience. Section 3 presents a risk-informed performance-based approach to evaluate and differentiate levels of compliance against the first basic requirement laid down by the Regulation (EU) No 305/2011 of the European Parliament and of the Council, i.e., mechanical resistance and stability, and ISO 15928 requirements for the structural safety (ultimate limit states) and structural serviceability (serviceability limit states) of building structures. Section 4 presents a summary of the proposed approach and its practical application for designers to assure the resilience and reliability of building structures against natural risks. The concluding remarks are presented in Section 5.

2. Natural Disasters and Resilience of the Built Environment

According to some authors [11], one of the most important dimensions of future-proofing for the building environment is resilience to unexpected or uncontrollable events and circumstances or the ability to maintain and/or resume normal operations during/after an adverse event (e.g., climate change, seismic events, floods, terrorist actions). Resilience is the ability to resist, absorb, accommodate, adapt, transform and recover from the effects of a hazard. It is necessary to make its relation to disaster risk management explicit, in relation to natural disasters that affect the built environment. This is the case of wind, water, or geoseismic actions acting on building structures. Wind actions may include cyclones, tornados or downbursts. Water agents include extreme precipitation phenomena, floods and tsunami. Geoseismic agents include earthquakes, volcanos and landslides.

Recently, resilience management research applied to the building environment has attracted considerable interest [13,23–29], with various studies seeking to understand the cost/benefit of building resilience design and establish resilience assessment systems for buildings [8,30,31].

The frequency of natural disasters, especially those linked with the climate changes, has increased globally in recent years, with adverse consequences for human life and property and sustainable economic and social development. Looking ahead, natural disaster risk is expected to continue to rise, for example, due to climate change and increased exposure and vulnerability caused by rapid increase in technological dependencies and massive urbanization. Natural agents such as temperature changes, extreme precipitation and wind can have a high impact on buildings. The global seismic risk remains severe and it is challenging to assure resilience with regard to this particular disaster risk [32]. With the rapid increase of intricate new interdependent infrastructure networks and construction in general in the last few years, an increasing amount of the world population and property will be exposed to seismic risks. At the same time, the natural aging process of constructed assets also impairs the seismic safety and serviceability of the existing buildings. In certain recent earthquakes, although some buildings did not collapse, they could hardly be repaired due to severe damage, causing substantial economic losses and enormous social impacts.

The resilience of the built environment is often linked with policymaking and strategies in the aftermath of catastrophic or traumatic changes [6,7,9,10]. It is a multidimensional concept covering physical (e.g., quality of building design and construction), infrastructural (e.g., lifelines), environmental (e.g., natural disasters), economic-social (e.g., impacts on local communities), political-regulatory (e.g., building codes and standards) and organizational aspects (e.g., decision-making strategies) [8].

Indeed, there is a need to assess how these broad and new resiliency and sustainability objectives may interact with existing traditional building regulatory objectives, namely if introduced in a rather short period of time, regarding the potential result in increased hazards and risks to the buildings occupants [27,33].

It is worth noting that the Consortium of European Building Control concluded that if only one task could be performed by the building control authority's available resources, then the focus should be the first basic requirements for construction works established by European regulations, i.e., structural performance. There is a strong awareness about the need to develop clear, well-supported, and quantified performance criteria for use in building codes and, in this context, to explore whether a clear link between risk and performance requirements can be established [34].

3. Rating System for Building Structural Safety and Serviceability

3.1. Risk-Informed Performance-Based Building Structures

In the second half of the twentieth century, a gradual transition from a prescriptive to a performance-based building environment [2]. This led to a consensus on the basic performance requirements that should be met by publicly or privately promoted building projects. Such requirements are laid on transnational performance-based regulations or by national performance-based regulatory systems as well as by non-mandatory international standards [35,36] (Roostaie, et al., 2019; Saunders and Becker, 2015).

Building stakeholders in general and building end-users in particular, want to understand the underlying reasoning of the technicalities of the building codes and standards. Engineering disciplines use a combination of performance and risk concepts to address this explicitly [37–40]. In addition to empowering authorities, end-users and other stakeholders to make risk-informed decisions about the levels of performance they require, the integration of risk information into performance-based building environments also improves the communication between construction-related markets such as housing, manufacturing, property, finance and insurance [3].

Risk-informed performance-based regulations enabled a major step forward in the building AECO sector, following what is already common practice in the manufacturing sector [3]: (i) performance certification of the delivered product, with the ultimate goal of certification of the whole building; (ii) as well as with "satisfaction guaranteed", including financial warranties or insurance that cover failures of the building stock and an adequate response with the prompt recovery from its consequences. Assuring the simultaneous fulfilment of the needs of the different building projects stakeholders is nevertheless challenging.

Building performance certificates are an appropriate means of communicating technical information throughout the building assets value chain (Almeida et al. 2015), facilitating assessment on the side of "demand" and increasing the acceptance of the marketing strategies on the side of "supply" [41–43]. These certificates usually cover the technical attributes that are most valued by end-users, i.e., the major societal concerns such as safety and health, and environmental protection [42–44]. LEED, BREEM, GREENSTAR, CASBEE, or DBNG are examples of popular building performance-based evaluation schemes [45–47]. A more detailed analysis of the implications of the different types of demonstrations of conformity of buildings (e.g., engineering performance certificates and risk reports related to contractual or other legal guarantees against building nonconformities) and the extent to which these integrate the core engineering risk parameters established in the regulations and standards of the building design processes have been discussed elsewhere [3,5].

End-users needs are at the top of the hierarchy of building performance requirements [3,28]. These needs include, in a general and definitive way, the essential interests and expectations of society in general (reflected in technical regulations) and others related to individual expectations. End-user needs can be formulated in the following ways [1,5]: (i) in the form of a generic statement that can include the fundamental aspects valued by the end-users (society in general and stakeholders, including individuals) or (ii) in a way that characterizes the performance of the building required to be considered by the user as satisfactory, namely through the naming of qualitative attributes.

The set of indicators that better translate end-user needs and expectations should be carefully selected and supported [48]. For example, in European Union (EU) this set should include at least the basic requirements for construction works laid down by the Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonized conditions for the marketing of construction products: (i) mechanical resistance and stability; (ii) safety in case of fire; (iii) hygiene, health and environment; (iv) safety and accessibility in use; (v) protection against noise; (vi) energy economy and heat retention; vii) sustainable use of natural resources. One can also take into consideration the framework for specifying the performance of buildings established in the international standards ISO 15928 and ISO 19208, which expands and further detail some of the requirements mentioned above [32]. For example, ISO 19208 mentions contributions to: (i) sustainable development at the level of use of resources, such as energy and water; (ii) choice of building materials; (iii) choice of construction methods and resources; (iv) waste disposal and resilience.

3.2. Evaluating Building Structural Safety and Serviceability against Natural Disasters

In relation to the first basic requirement laid down by the Regulation (EU) No 305/2011 of the European Parliament and of the Council, i.e., mechanical resistance and stability, the needs of end-users can be formulated by generic statements containing relevant aspects valued by end-users in terms of structural performance or by using qualitative attributes to be met by building structures. These statements can be formulated, for example, as follows [1,14]: (i) safety of structures, protection of people and goods, trustworthiness in commercial transactions [49]; (ii) protection of human lives, limitation of economic losses and maintenance of important civil protection facilities (Eurocode 8); (iii) safety of the occupants of the house [50]; (iv) acceptance, by part of the occupants, of the functioning and appearance of the dwelling and its components, of the activities of the other occupants, of the functioning of the equipment in the dwelling, the comfort provided and the real state value of the dwelling [51]; (v) acceptance, by part of the occupants, of the level of safety and structural serviceability of the dwelling throughout the agreed life span [52]; (vi) protecting the lives of the occupants, preventing injuries to occupants, safeguarding property and property [40]; (vii) protection of human life, safeguarding property, maintaining functionalities and other objectives expected from the building [53].

Tables 1 and 2 present a list of risk-informed performance-based metrics for evaluating the structural safety and serviceability of constructed assets against natural disasters. These metrics comprise two categories of technical parameters: (i) parameters for the description of technical performance; and, (ii) parameters for the description of the inherent technical risk. These parameters express in a quantitative manner both the agents that act on and/or qualitatively affect the technical behavior of the building (parameters describing technical performance) and the uncertainty associated with achieving performance and/or behavior (parameters describing inherent technical risk). A complete list of parameters that can be used to describe the structural performance and a detailed explanation of the underlying principles for their choice is presented elsewhere [1].

Table 1. Metrics for evaluating building structural safety against natural disasters.

Agent	Parametrization
Wind actions	Representative value of wind speed (or dynamic wind pressure) Annual probability of occurrence (or average return period) Parameters for differentiating reliability (partial safety factor γQ, multiplication factor K)
Snow actions	Representative values of snow accumulation (meteorological data or characteristic snow load at ground level) Annual probability of occurrence (or average return period) Parameters for differentiating reliability (partial safety factor γQ, multiplication factor K)
Seismic actions	Representative value of seismic activity (effective peak ground acceleration, ground acceleration response spectrum or others) Probabilities of occurrence (or average return periods) Parameters for differentiating reliability (importance coefficient γI, multiplication factor K)
Other actions	Representative parameters of other actions

Table 2. Metrics for evaluating building structural serviceability against natural disasters.

Agent	Parametrization
Wind actions	Same as Table 1
Snow actions	Same as Table 1
Seismic actions	Same as Table 1 Floor acceleration response (for equipment and non-structural components)
Other actions	Same as Table 1

The rating scales presented in Table 3 can be used to measure and compare the performance levels of new and existing buildings. These scales enable [3,54]: (i) communication with plain language that can be easily understood by the "demand" side without the need to make technical judgements; (ii) evaluating the conformity of the "supply-side" during the building design; (iii) establishing the level of effort and resources needed to control deviations during the design, construction and use phases.

For new buildings, rating scales should be calibrated with an inferior threshold linked with the minimum mandatory requirements of the building codes (class B). Below this threshold, end-users are exposed to unacceptable levels of risk. It may be convenient to establish a superior threshold (e.g., class A) when it is advisable to make it publicly known that it is impossible to achieve the highest possible level of technical performance. It should be possible to program different performance levels for each performance attribute (e.g., class A for structural safety and class B for structural serviceability). Each class must be linked with given values for the engineering variables listed in Tables 1 and 2 that relate to the building attribute (e.g., class A for structural safety relates with buildings that withstand wind loads equal to those generated with a return period higher than the legal minimum, e.g., 2500 years) [37]. The following sections detail how this can be achieved for each agent of natural disaster risks.

Table 3. Calibration principles for rating scales, adapted from ISO 11863.

New Buildings		Existing Buildings	
Class	**General Calibration Rule**	**Rating**	**General Calibration Rule**
A+	Exceptionally demanding	9	Exceptionally demanding or non-applicable
A	Clearly above average, but not the exceptionally demanding	[7,9]	Clearly above average, but not the exceptionally demanding
B	Typical mid-range or normal	[5,7]	Typical mid-range or normal
C	Unacceptable in any circumstance	[3,5]	Clearly below average, but acceptable under justified circumstances
D	Unacceptable in any circumstance	[1,3]	Exceptionally below average, but acceptable under exceptional and justified circumstances
N/A	Non-applicable	0	Unacceptable, not required or non-applicable

3.3. Wind

The natural actions of the windfall under the category of fixed variable actions (Q) according with Eurocode 1 [55,56].

The representative value of the wind speed is a parameter (for the description of technical performance) that allows the wind actions to be described that produce effects such as [57]: (i) excessive forces or instability in the structural and non-structural elements; (ii) excessive deflection or distortion of the structure or its elements; (iii) repeated dynamic forces causing fatigue of structural elements; (iv) aeroelastic instability, in which motion of the structure in wind produces aerodynamic forces augmenting the motion; (v) excessive dynamic movements causing concern or discomfort to occupants or onlookers and/or; (vi) effects of interference from existing and potential future buildings. This wind speed value can be expressed in different ways, namely [50,51]: (i) 3 sec gust [3-s gust]; (ii) 1 min mean [1-min mean]; (iii) 10 min mean [10-min mean]; (iv) hourly mean.

The ISO 4354 [57] standard provides guidelines for converting the various forms of expression of wind speed and describes the process of converting these speeds to forces.

As an alternative to the representative value of wind speed (m/s), the dynamic wind pressure (kPa) can also be considered as a parameter (for the description of technical performance) to describe the wind action [50,51,55,57]. In fact, in accordance with the Structural Eurocodes, the effects of these pressures (or forces) represent only the extreme effects of the wind [55], since the wind actions act directly as pressures on the external surfaces of closed structures and, due to the porosity of the external surface, also indirectly on the internal surfaces [55]. However, considering that either of these two alternatives can be converted into the other [57], the representative parameter of the internationally standardized wind action is the wind speed [50,51].

According to the Structural Eurocodes, the basic wind speed v_b is calculated as given in Equation (1) [55].

$$v_b = c_{dir}\, c_{season}\, v_{b,0} \tag{1}$$

where (i) $v_{b,0}$ is the fundamental value for the basic wind speed to be indicated in each National Annex to the Structural Eurocodes and which consist of the characteristic value of the average speed referred to at 10 min time intervals, regardless of the wind direction and the time of year, at 10 m height in open terrain and low vegetation and with isolated obstacles separated by distances greater than 20 times the height of these obstacles [55]; (ii) c_{dir} is the directional factor to be indicated in the National Annex to Structural Eurocodes, with the recommended value of 1.0) [55]; (iii) c_{season} is the seasonal factor to be indicated in the National Annex to Structural Eurocodes, with the recommended value of 1.0) [55].

When actions can be evaluated statistically (as is the case with environmental actions, and in particular the action of the wind), the calculation values can be expressed in terms of the probabilities of occurrence (i.e., the inverse of the return periods) [58]. The mean return period, defined as the average duration between consecutive occurrences, is an equally valid form of expression in many cases [59].

In the Structural Eurocodes, the characteristic values of the basic values v_b and $v_{b,0}$ (according to the recommendation of the Structural Eurocodes $v_b \approx v_{b,0}$) presents annual probabilities of exceedance of 0.02 [56], i.e., they have a mean return period of 50 years [55]. In general terms, return periods between 50 and 100 years provide reasonable values for characteristic values of common buildings [59]. The values presented in Table 4 allow the basic wind speed $v_{b,n}$ with a mean return period n to be estimated using the semi-empirical expression (2) adopted from [60] and [55].

$$v_{b,n} = v_{b,50}\, c_{\text{prob}}, c_{\text{prob}} = \left(\frac{1 - \text{K}\ \ln(-\ln(1 - p))}{1 - \text{K}\ \ln(-\ln(0,98))}\right)^{\text{n}} \tag{2}$$

where p is the annual probability of occurrence and K and n are constants whose recommended values are, respectively, 0.2 and 0.5 [55].

Table 4. Indicative values of the modification coefficient of the basic wind speed $v_{b,n}$.

Medium Return Period (*n* Years)	**2**	**5**	**10**	**50**	**100**	**200**	**500**	**1000**	**2500**
Annual probability of occurrence p	0.5	0.2	0.1	0.02	0.01	0.005	0.002	0.001	0.0004
Modification coefficient c_{prob}	0.77	0.85	0.90	1	1.04	1.08	1.12	1.16	1.20

The annual probability of occurrence of the basic wind speed influences the entire procedure for calculating the pressures and forces resulting from the action of the wind, as specified in the Structural Eurocodes [55]. These probabilities are difficult to estimate and there is a degree of uncertainty associated with them, as in the estimation of any quantity in the engineering disciplines and particularly in the calculation of wind actions. This degree of uncertainty can be considered through the reliability theory if the statistical properties of the variables are known [57]. A particular way of considering these uncertainties is given in Equation (3) [56,57,59].

$$\text{Q}_{\text{d,w}} = \gamma_{\text{q}}\, \text{Q}_{\text{rep,w}} = \gamma_{\text{q}}\, \psi\, \text{Q}_{\text{k,w}} \tag{3}$$

where [56]: (i) $\text{Q}_{\text{d,w}}$ is the design value for the wind action w; (ii) γ_{q} is the partial safety factor that takes into account the possibility of unfavourable deviations of the action values from the representative values; (iii) $\text{Q}_{\text{rep,w}}$ is the representative value of the wind action w, that is, the magnitude of the wind load; (iv) $\text{Q}_{\text{k,w}}$ is the characteristic value of the wind action w that derives from the basic values of wind speed (or dynamic wind pressure); (v) ψ = 1.00, $\psi = \psi_0$, $\psi = \psi_1$ ou $\psi = \psi_2$ [56,58].

Similar to what is considered for other variable actions [14] conservative simplifications can be suggested to affect the values of $\text{Q}_{\text{rep,w}}$ by the partial safety factor γ_{Q} ($\text{Q}_{\text{d,w}} = \gamma_{\text{q}}\, \text{Q}_{\text{rep,w}} \approx \gamma_{\text{Q}}\, \text{Q}_{\text{rep,w}} \approx \gamma_{\text{Q}}\, \psi\, \text{Q}_{\text{k,w}}$) established in the Structural Eurocodes [56,58]. Also, as for other types of permanent and variable actions, these partial safety factors γ_{Q} can be affected by multiplicative factors K [56,59] and exclude differentiation strategies based on direct variation in reliability indices β or the probabilities of failure. This excludes modification of the coefficients ψ and it is suggested to consider the recommended values of the regulations [56].

In view of the above, the differentiation of structural safety and serviceability can be based on the following two differentiation strategies: (i) use of multiplicative factors (K $\neq$ 1.0) modifying the partial safety factor γ_{Q}; (ii) alteration of the probabilities of occurrence associated with the parameters (describing technical performance) describing the wind action.

This means that, for example, for the case of ultimate limit states, a return period of 500 or 1000 years can be established as the representative value of the wind action together with a partial safety factor of 1.0 or, alternatively, a return period of 50 years can be used as the representative value of the wind action with a partial safety factor of, for example, 1.3 or 1.5 [50]. Similarly, for the serviceability limit states, a return period of 20 years can be used as a representative value of the wind action together with a partial safety factor of 1.0 or, alternatively, a return period of 50 years can be used as a representative value of the wind action with a partial safety factor of, for example, 0.7 [51]. The choice of values for the wind action combined with the choice of the level of reliability associated with the structural calculation is the usual method to establish the level of structural reliability (and of the structural performance under the wind action) [57]. To illustrate this method, Table 5 has been taken from [57] and [58]. The classification of importance groups presented in this table corresponds to the classification established in [58] and [56]. The minimum and maximum annual probabilities of occurrence are suggested with reference to [57] and [58], respectively. The reliability indices (failure probability) required for a given wind condition follow the minimum values specified in [57].

Table 5. Indicative relationship between the importance of the structure, the structural reliability and the design value for the wind action.

Importance Group	Reliability Index (Probability of Failure)	Annual Probability of Occurrence of the Design Value of the Wind Action
I	2.3 (10^{-2})	1:200 to 1:500
II (current situation)	3.1 (10^{-3})	1:500 to 1:1000
III	3.7 (10^{-4})	1:1000 to 1:2500
IV	4.2 (10^{-5})	Determined case by case

After defining the required reliability index (e.g., for the normal situation corresponding to that for which the Structural Eurocodes are calibrated), the design value of the wind action can be determined by selecting a safety factor combined with the representative value of the appropriate wind action. This is the European method [57].

Thus, performance class B should reflect the normal situation established at a regulatory level, namely the admission of the values of the basic variables published in the National Annexes of the Structural Eurocodes and the aspects corresponding to the reliability class RC2 of the same regulation (K_B = 1.0) [56]. For performance class A, a mean return period of the representative wind speed value higher than the value specified by the regulation (for example, the double) may be allowed. For performance class A+, it must be ensured that, at least, it is used for design value $Q_{d,w}$, which results from the increase in the regulated partial safety factor γ_Q with a multiplicative factor K_{A+} = 1.1. It should be noted as an indication that the highest performance class considered in the Japanese regulation [61] considers an increase of 20% compared to the normal situation. The simultaneous use of the two strategies for differentiating structural reliability (return period and K) must be accurately assessed, taking into account the consistency of the overall reliability obtained. Both the values suggested for the multiplication factor K_{A+} and those suggested to modify the average return period are indicative.

The technical evaluation of structures of an unusual nature, dimension, or complexity and particularly sensitive to wind (e.g., too flexible, slender, tall, light, or of peculiar geometry) may require additional engineering studies [57]. Due diligence should be taken in the direct application of the proposed evaluation criteria.

3.4. Snow Action

Snow action should be classified as variable action because it presents a variation of magnitude in time that is not negligible or monotonic as fixed actions because it presents a distribution and fixed positioning in the structure [56,62,63]. However, depending on the geographical location, the Structural Eurocodes also consider the possibility of treating this type of action as an accidental action [56,62] in cases where snow loads at the ground level are due to snow accumulations with an exceptionally unusual probability of occurrence [62,63] and/or when the snow deposition pattern in roofs also has an exceptionally infrequent chance of occurrence [62,63].

In this paper, snow actions are considered as variable actions under normal conditions [62]. The exceptional conditions that prompt snow actions to be classified as accidental actions are excluded in this paper.

Snow actions can be described using a set of representative values. The ISO 15928-1 [50] standard suggests parameters for the description of technical performance based on meteorological data, namely: (i) snow height at ground level (m); (ii) snow density (kg/m^3); (iii) snow accumulation period (days/year).

The representative value of the height of the snow at ground level derives from the basic height of the snow duly modified according to local factors such as zoning of the territory, exposure or topography [50]. The ISO 4355 [64] standard presents expressions that allow relating the snow density ρ with the height of the snow at ground level, with the average temperature during the snow accumulation period and with the average wind speed during the same period. The representative value of the snow density is the average value used in converting a given height of snow into the respective snow load [50].

Technical regulations developed in countries such as the United States of America, Russia or Japan make it possible to relate the density of snow to the height of snow at ground level and the latter with the characteristic value of snow load at ground level [64]. For example, the North American standard ANSI/ASCE 7-88 presents the relationship $s_{50} = 1.91\ (d_{50})^{1.33}$, where s_{50} is the snow load at ground level (kPa) with a return period of 50 years and d_{50} is the height of snow at ground level (m) with a return period of 50 years. However, other international standards state that data on equivalent water mass in snow, which can be collected at weather stations, is preferable to data on the height of snow at ground level, namely to determine the characteristic value of the snow load at ground level [64]. The design procedures established in the Structural Eurocodes, in turn, use snow load values [62] and do not provide guidelines to incorporate calculation methods based on meteorological data such as the height of snow at ground level or the period of snow accumulation, although they provide average values recommended for snow density [62].

For practicality, the characteristic value of the snow load at ground level as a representative value of the snow accumulation is used (as an alternative to the meteorological data from which it derives). The approach harmonized by the Structural Eurocodes to determine the characteristic value of the snow load at ground level uses zoning maps of the territory [62] and expressions that allow for that determination according to the established zoning and the altitude [62]. In the case of the Iberian Peninsula, the applicable expression is:

$$s_k = (0.190\text{Z} \ - 0.095)\left[1 + \left(\frac{\text{A}}{524}\right)^2\right] \quad (4)$$

where: (i) s_k is the characteristic value of snow load at ground level (kN/m^2); (ii) A is the altitude above sea level (m); (iii) Z is the number of the sea level map zone (1, 2 or 4) [62].

The characteristic values of snow load at ground level *sk* thus determined excludes exceptional snow load [62], which, as mentioned above, must be properly treated as accidental actions. The characteristic values of snow load at ground level *sk* are the result from the statistical treatment of meteorological data [64]. When actions can be evaluated statistically, the respective calculation values can be expressed in terms of the probabilities of occurrence (i.e., the inverse of return periods) [58]. The Structural Eurocodes establish for these characteristic values *sk* an annual probability of occurrence of 0.02 [62], that is, a mean return period of 50 years [56].

The characteristic values of snow loads at ground level $s_{k,n}$ (kN/m^2), with a generic mean period of n years, can be determined from the characteristic values $s_{k,50}$ using Equation (5).

$$sk,n = sk,50\ c_{prob} \tag{5}$$

where c_{prob} is the modification coefficient of the characteristic snow load value at ground level $s_{k,50}$ obtained with Equation (6). This equation should not be used for probabilities of occurrence greater than 0.2 (i.e., return periods with less than 5 years) [62]. However, some authors use this expression for probabilities of occurrence of 0.5 [65].

$$c_{prob} = \left\{ \frac{1 - \mathrm{Vs}\,\frac{\sqrt{6}}{\pi}[\ln(-\ln(1-p)) + 0.57722]}{1 - \mathrm{Vs}\,\frac{\sqrt{6}}{\pi}[\ln(-\ln(0.98)) + 0.57722]} \right\} \tag{6}$$

where p is the intended annual probability of occurrence (approximately equivalent to $1/n$) and Vs is the yearly variation coefficient of the maximum snow load [62,65]. Figure 1 graphically represents Equation (6). Table 6 is adapted and expanded from [65] and presents some estimates for the modification coefficient c_{prob} assuming an annual variation coefficient Vs = 0.2.

Table 6. Modification coefficient for the characteristic value $s_{k,50}$ of the snow load at ground level.

Mean Return Period (*n* Years)	**2**	**5**	**10**	**50**	**100**	**250**	**500**	**750**	**1000**
Annual probability of occurrence p	0.5	0.2	0.1	0.02	0.01	0.004	0.002	0.0013	0.001
Modification coefficient c_{prob}	0.64	0.75	0.83	1	1.07	1.17	1.24	1.28	1.31

Structural Eurocodes provide for the possibility of considering different probabilities of occurrence when calculating snow load values at ground level [62]. For the case of snow accumulation, it can be considered that the probability of occurrence of the calculation values is the same as the probability of occurrence of the respective characteristic values. Therefore, the probability of occurrence (and the return period) of the snow load value at ground level can be used as a strategic parameter for differentiating reliability (parameter for the description of the inherent technical risk).

From the appropriate modification of these snow load values at ground level (s_k or s_n), according to the calculation procedures specified in the Structural Eurocodes [62] or in other international standards [64], the intensity and distribution patterns of the snow load on the roofs can be defined, as deduced from the simplified expression (7).

$$s = s_k\ \mu\ ou\ s = s_n\ \mu \tag{7}$$

where s is the value of the snow load on the roofs (kN/m^2), fundamental for the purposes of structural design [62], and μ is a function that depends on factors such as geometry and thermal and physical properties of the roof, the characteristics of the surrounding terrain and the proximity of obstacles to snow accumulation, as well as the weather conditions [62,64].

The measurements that generate the basic data on the snow action depend heavily on the observation method and the exposure of the area where the data collection is carried out. The classification of information about a climatic zone, according to the characteristics of the specific region that generates that information, must be weighted accordingly [64], since it always has a certain degree of uncertainty. A particular way of considering this type of uncertainty is using Equation (8) [56,59].

$$\mathrm{Q_{d,S}} = \gamma_\mathrm{q}\ \mathrm{Q_{rep,S}} = \gamma_\mathrm{q}\ \psi\ \mathrm{Q_{k,S}} \tag{8}$$

where [56]: (i) $Q_{d,S}$ is the design value for the snow action *S*; (ii) γ_q is the partial safety factor that takes into account the possibility of unfavourable deviations from the values of the actions in relation to their representative values; (iii) $Q_{rep,S}$ is the representative value of the snow action *S*, that is, the magnitude of the load due to snow accumulation; (iv) $Q_{k,S}$ is the characteristic value of the snow action *S* that derives from the snow load value on the roofs *s*, as previously defined and; $\psi = 1.00$, $\psi = \psi_0$, $\psi = \psi_1$ or $\psi = \psi_2$ [56,58,62].

On the other hand, there are also uncertainties associated with the coefficients and models used to transform meteorological data into actions that can be incorporated into design procedures and engineering calculations. In this context, a conservative simplification is suggested to affect the values of $Q_{rep,S}$ by the partial safety factor γ_Q (that is, $Q_{d,S} = \gamma_q\, Q_{rep,S} \approx \gamma_Q\, Q_{rep,S} \approx \gamma_Q\, \psi\, Q_{k,S}$) established in the applicable regulation [56,58]. These partial safety factors γ_Q can also be affected by multiplicative factors K [56,59] and exclude methods based on direct variation in reliability indices β or failure probabilities. The modification of the coefficients ψ is also excluded, suggesting that the recommended values or regulations are considered [56] (A.1.2.2). These partial safety factors γ_Q and these multiplicative factors K can also be used as strategic parameters for differentiating reliability (parameters for describing the inherent technical risk).

The choice of values for the representative parameter of snow accumulation (parameter for the description of technical performance)—a characteristic value of snow load at ground level s_k—must be combined with the annual probability of occurrence selected according to the importance of the structure in question, as shown in Table 7. The suggested evaluation criteria for performance classes A+, A and B consider the recommendations of the international standard ISO 22111 [58] and the considerations of Japanese regulation [61]. The classification of importance groups is based on [56,58].

Table 7. Indicative relationship between importance of the structure and design value for the action of snow [58,61].

Importance Group	Annual Probability of Occurrence of the Calculation Value of the Snow Action
I	1:250
II (normal situation)	1:500
III	1:750
IV	Determined case by case

In addition to the variation in the probability of occurrence, it is suggested that $K_{A+} = 1.1$ corresponding to the reliability class RC3 established in the Structural Eurocodes [56]. It should be noted as an indication that the highest performance class considered in Japanese regulation [61] considers an increase of 20% compared to the normal situation.

3.5. Seismic Action

Seismic activity can be treated as variable actions for presenting a variation of magnitude in time that is not negligible or monotonic [56], or as accidental actions for having a short duration but a significant magnitude not likely to occur during the agreed useful life period [56].

The classification of this type of actions is important, as it may affect the strategy of combining this with other types of actions [66]. The classification, as in the case of snow and wind, depends on the information available on the statistical distributions of these actions and the location of the affected structure [56,59,66]. For example, seismic actions can be considered as accidental actions in regions where seismic activity is low [66].

Within the scope of Structural Eurocodes, actions that derive from land movements with seismic origin enjoy a specific definition [56] and treatment [67]. The Structural Eurocodes also recognize that the seismic action varies considerably depending on the seismic-genetic characteristics of the regions [67]. The determination of this type of actions must consider factors such as the seismicity of the region, the local site characteristics and the dynamic characteristics of the structure [50], as well as the importance of the structure with regard to its use during and after the seismic event and also the spatial variation of seismic movements [66].

The way of describing and framing seismic actions in regulatory terms is not fully harmonized. Some international standards highlight the following parameters for describing technical performance: (i) effective peak ground acceleration (% of gravity); (ii) ground acceleration response spectrum; (iii) base shear coefficient; (iv) lateral force (kN). For the case of the serviceability limit states, and in situations where equipment or installations cannot be used due to accelerations, the floor acceleration response [50] should also be included as a basic parameter.

As will be seen below, effective peak acceleration of the soil is a fundamental parameter not only to describe seismic actions but also to differentiate reliability. In particular, in order to harmonize the determination and zoning of seismic hazard, it is expected that the description of seismic movements will increase based on the effective acceleration of peak land corresponding to a mean return period of 475 years [68]. On the other hand, the acceleration response spectrum makes it possible to evaluate the performance of any type of buildings and is closely related to the first parameter [69]. For this reason, it is considered preferable to highlight these two types of parameters at the expense of the others.

The reference method for determining the effects of seismic actions is the modal analysis considering a the design response spectrum $S_d(T)$ [66,67]. The calculation of the response spectrum, as considered in the Structural Eurocodes [67], consists of a relative reduction in the elastic response spectrum of the acceleration *Se(T)*, a reduction that aims to avoid an explicit inelastic analysis of the structure [67,69]. This reduction is achieved, among others, by considering a behaviour coefficient of the structure q that characterizes the relationship between the resistant capacity and the energy dissipation capacity of the structure [67]. The elastic response spectra of acceleration $S_e(T)$—that can be converted into elastic displacement response spectra $S_{De}(T)$ [67] and represents the horizontal component of the seismic movement [67] and has a similar shape for both the ultimate and serviceability limit states. This means that the seismic displacements from a given point on the surface must be represented by one or more parameters of this type. The normalized form (see Figure 2) of these elastic acceleration response spectra $S_e(T)$ depends on the value of the calculation acceleration a_g on type A soil, the lower limit of the constant acceleration section T_B, the upper limit of the constant acceleration section (and the lower limit of the constant speed section) T_C, of the value that defines the beginning of the constant travel section (and the end of the constant speed section) T_D, the terrain factor S and the damping factor η, as defined in the Eurocode 8 National Annexes. The shape of the calculation response spectrum considered in the Structural Eurocodes derives from the standardized shape of the elastic acceleration response spectra presented in Figure 3 and, generally, from the considerations about standardized design response spectra [66].

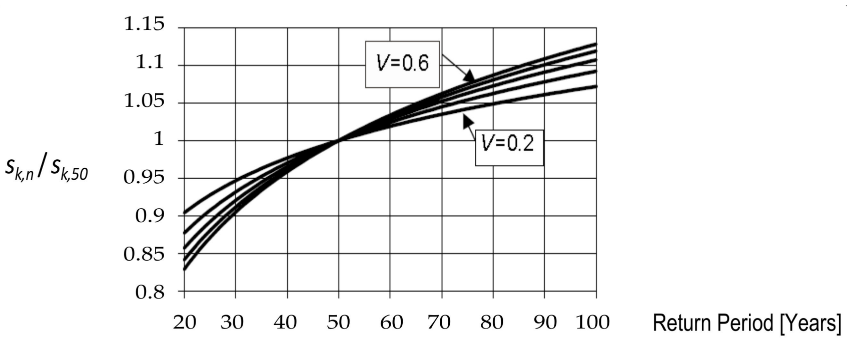

Figure 2. Adjustment of snow load at ground level according to the return period [62].

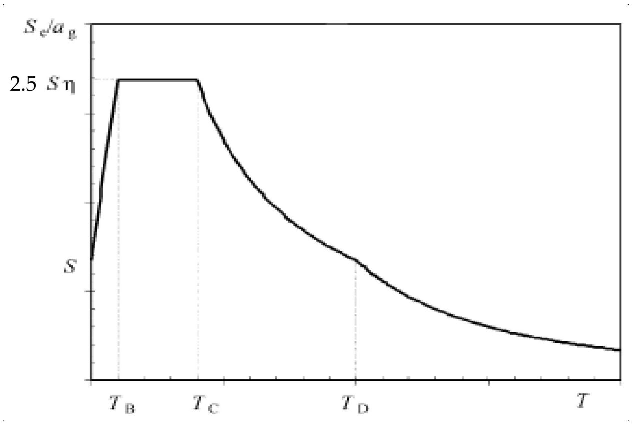

Figure 3. Shape of elastic acceleration response spectra $S_e(T)$ [67].

The values of the periods T_B, T_C e T_D and the S factor depend on the characteristics of the soil. The correction factor η depends on the dynamic characteristics of the structure. The value of the calculation acceleration a_g can be determined through the expression (9) [67].

$$a_g = \gamma_I \, a_{gR} \tag{9}$$

where a_{gR} is the effective peak ground acceleration of the reference soil for type A soil and γ_I is the importance coefficient, that is associated with the different classes of importance of the structures and the consequences of structural and non-structural failures [67].

Acceleration a_{gR} is a fundamental data base (parameter for the description of technical performance) related to the induced seismic forces that are used in the seismic design procedures of structural subsystems, since this acceleration a_{gR} depends on the shape of the design response spectrum [69]. Acceleration a_{gR} must be established in the National Eurocodes Annexes [67] in accordance with the T_{NCR} reference return period (recommended value of 475 years) or, equivalently, the reference probability of occurrence of P_{NCR} in 50 years (recommended value of 10% in 50 years).

When the basic parameters (such as acceleration a_{gR}) can be evaluated statistically, it is possible to use probabilities of occurrence or return periods as strategic parameters for differentiating reliability (parameters describing inherent technical risk).

Figure 3 describes the exposure of a given location to a given seismic phenomenon. In the Figure 4, a_{gR} (10% probability of occurrence over a 50-year period) is ~0.16 g, and an effective peak acceleration of the terrain of 0.10 g will occur with probabilities of ~0.004 and ~0.20 for periods of 1 and 50 years, respectively [68].

Another strategic parameter for differentiating reliability (parameters describing inherent technical risk), which is perhaps more intuitive and easier to implement in practice because it relates to calculation procedures (namely those that fall within the scope of dynamic analysis of the structures) [66], is the importance coefficient γ_I. The values of the importance coefficient γ_I are associated with building importance classes and must correspond to a return period of the appropriate seismic event for each of these important classes [67]. The importance classes presented in Table 8 correspond approximately to the consequence classes established in the Structural Eurocodes [56,67] and in other normative references [58]. Although the calculation of the values for the coefficients γ_I be avoided in the Structural Eurocodes The value of γ_I so that the probability of occurrence of the seismic action P_L in T_L years is the same as the probability of occurrence defined for the reference seismic action P_{LR} in T_{LR} years can be estimated using the expression (10).

$$\gamma_I \sim (T_{LR}/T_L)^{-1/k}, \text{ for } P_{LR} = P_L \tag{10}$$

where the value of k depends on seismicity and is usually of the order of 3 [67]. Alternatively, to achieve a probability of occurrence of seismic action P_L in T_L years different from the probability of occurrence of the reference seismic action P_{LR} in the same T_L years, the value of this coefficient can be estimated using the expression (11).

$$\gamma_I \sim (P_L/P_{LR})^{-1/k} \quad (11)$$

where k has the same meaning [67].

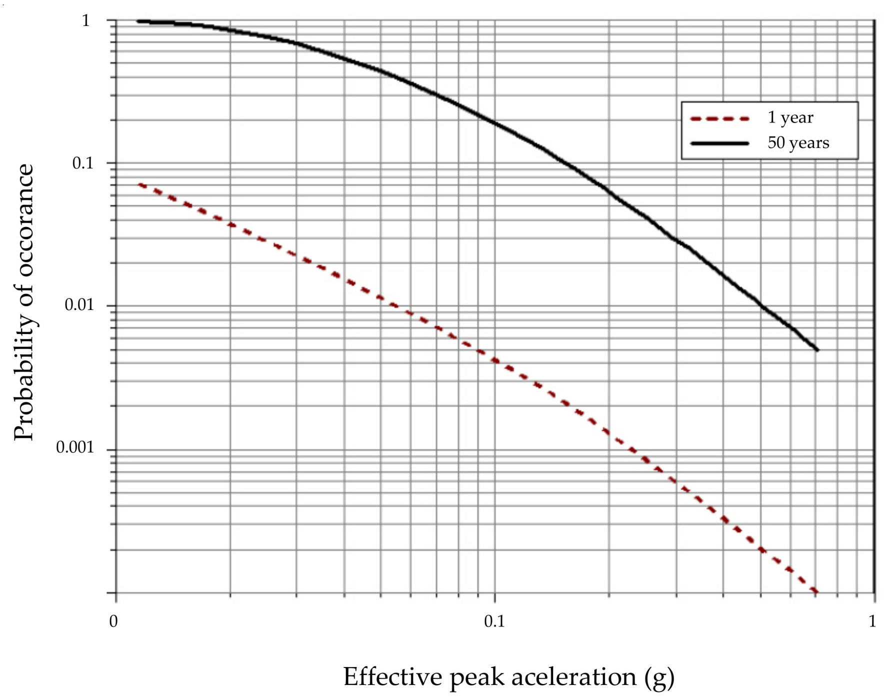

Figure 4. Example of hazard curves for a given location for reference periods of 1 and 50 years [68].

Table 8. Values of the importance coefficient γ_I as a function of the building importance [67].

Importance Class	γ_I
I	0.8
II	1.0
III	1.2
IV	1.4

The probability of occurrence P_R in T_L years of a specific level of a seismic action and the mean return period T_R of the same level of seismic action are related through the expression $T_R = -T_L/\ln(1 - P_R)$ [67,68]. The modification of the probability of a reference P_{NCR} associated with seismic action for a period of 50 years (or the equivalent reference return period T_{NCR}) is a regulatory differentiation strategy for reliability [67]. This means that the differentiation of reliability is not necessarily achieved by considering a particular structure in a class of greater importance than that corresponding to its real characteristics, as is done in North American regulations [69], but by modifying the level of risk underlying the objectives to be achieved (i.e., the average return period).

The different levels of structural reliability within each class of importance can thus be obtained by modifying this coefficient γ_I depending on different mean return periods T_R, according to the following expression (12) [68], and that is valid for a fixed period T_L of 50 years,

$$\gamma I \sim \left(\frac{P_R}{P_{NCR}}\right)^{-1/k} = \left(\frac{1 - e^{-T_L/T_R}}{P_{NCR}}\right)^{-1/k} \quad (12)$$

Table 9 exemplifies some values of γI for class II structures, modified according to different values of the probability of occurrence P_R in T_L = 50 years (i.e., the inverse of different values for the mean return period T_R).

Table 9. Modification of γ_I values for the differentiation of structural performance.

Performance Class	T_R	P_R	Estimation of Modified Values for γ_I						
			k = 2	k = 2.5	k = 3	k = 3.5	k = 4	k = 4.5	k = 5
B (ref.)	475	10%	1	1	1	1	1	1	1
A	1000	4.9%	1.43	1.33	1.27	1.23	1.20	1.17	1.15
A+	1500	3.3%	1.75	1.56	1.45	1.38	1.32	1.28	1.25

Risk-informed performance-based evaluation criteria may consider the value $T_{R(B)} = T_{NRC}$ = 475 years specified in the Structural Eurocodes, the value $T_{R(A)}$ = 1000 years recommended in the ISO 22111 [58] standard for importance class II and the value $T_{R(A+)}$ = 1500 years recommended in the ISO 22111 [58] standard for the importance class III. Table 10 assists in interpreting the practical meaning of these values [68]. It is relevant to note that the importance factor γ_I thus obtained plays a similar role to that of partial safety factors affecting the representative values of the actions as they aim to translate [66]: (i) the desired degree of reliability; (ii) the representative value of the intensity of the seismic movements; (iii) the variability of the seismic actions; (iv) the uncertainty associated with the modelling of the seismic actions and the structures themselves. This last consideration is explicitly confirmed in the Structural Eurocodes through the expression $A_{Ed} = \gamma_I \, A_{Ek}$, [67] where A_{Ed} is the design value of the seismic action and A_{Ek} is the characteristic value of the seismic action.

Table 10. Typical values and relationships between probabilities of occurrence and return periods.

Probability of Occurrence P_R	Period T_L	Mean Return Period T_R
10%	50 years	475 years
5%	50 years	975 years
10%	100 years	949 years
5%	1000 years	1950 years

Average return periods $T_{R(B)}$, $T_{R(A)}$ e $T_{R(A+)}$ are associated, respectively, with multiplicative factors K_B = 1.0, K_A = 1.25 e K_{A+} = 1.5. These multiplicative factors K have a function similar to that of the multiplicative factor established in the Eurocode [56]. The values adopted for each of the performance classes are approximations of the values calculated with expression (13).

$$K = \gamma I_{mod} / \gamma I_{reg} \tag{13}$$

where γ_{Imod} is the modified importance coefficient and γ_{Ireg} corresponds to the coefficient of importance recommended or regulated.

The proposed multiplications factor are identical to those established in the Japanese regulation [61], but they are merely suggestions that can be changed, since they are not based on any specific recommendations for a given national of regional context.

3.6. Other Actions

It is possible to parameterize natural intrinsic risks (quadrant A in Figure 1), which can be expressed through variable or accidental actions that somehow influence structural performance, both in terms of structural safety and serviceability, namely temperature variations, floods, tornadoes, tsunamis and objects dragged by the wind, among others [50,69,70].

In the absence of international normative references that systematize the evaluation of these "other actions", some guidelines for their possible consideration and future development as part of a structural performance rating system are presented.

3.6.1. Flooding

The flood height above ground and the flow speed can be used as representative parameters of the actions due to floods. These parameters allow to evaluate the structural consequences of this type of action [50,51]. As in the case of unstable soil, the construction of buildings in locations prone to flooding is an aspect that should be framed, in general terms, in the context of planning [50]. It should be noted, however, that information on the frequency of floods should be used to assess situations related to structural durability [50] and that this assessment may also be relevant in the context of structural safety and serviceability [50,51].

3.6.2. Temperature Variations

Structural subsystems, not exposed to daily variations, seasonal variations and/or relevant temperature variations may disregard the actions resulting in temperature variations [70]. However, actions due to temperature variations should be classified as indirect with regard to their origin and as variable actions because they present a variety of magnitude in time that is not negligible or monotonic and, as to the origin, as indirect [56,70]. As with other natural actions, the evaluation of this type of action can be based on statistical information related to basic data such as air temperature in the shade, solar radiation, etc. [70]. This means that, like other natural actions, the determination and evaluation of their calculation values can be expressed in terms of the probabilities of occurrence (i.e., the inverse of the return periods). For example, the characteristic values established for these actions in the Structural Eurocodes are generally calibrated for an annual probability of occurrence of 0.02 [70], which is equivalent to a return period average of 50 years [71]. Eurocodes also present expressions that allow the determination of the values of those actions for different annual probabilities of occurrence [70]. Like with other actions, it is possible to differentiate the performance of the structural subsystem by changing the probability of the action of temperature variations on the one hand, and/or affecting the safety coefficients γ_Q applicable to this type of actions through a multiplicative factor K.

4. Discussion

Table 11 summarizes the terms of reference for structural safety (related to the ultimate limit states) and structural serviceability (related to serviceability limit states) as described in this paper. These terms of reference comprise objective evaluation criteria, based on numerical values to be assigned to engineering or technical parameters that describe structural performance. The evaluation criteria are proposed for class II (CC2) structures in new buildings [3,37]. This proposal covers performance classes A+, A and B. The lower performance classes C and D may be admitted for existing buildings, but are considered unacceptable structural performance for new building structures [1]. These evaluation criteria must be reviewed and calibrated by the technical and scientific community before being incorporated into technical regulations and standards.

The practical meaning of the proposed evaluation criteria is that, for example, when considering wind actions, class A+ buildings shall withstand wind loads 10% higher than those with a return period higher than the legal minimum (e.g., 2500 years), while class A buildings building shall withstand wind loads equal to those generated with a return period higher than the legal minimum (e.g., 2500 years) and class B buildings shall withstand wind loads equal to those generated with the legal minimum return period (e.g., 1000 years). Likewise, class A+ buildings shall withstand seismic loads at least 50% above the legal minimum values, class A buildings shall withstand seismic loads at least 25% higher than legal minimum values and class B buildings shall withstand legal seismic loads defined.

Table 11. Terms of reference for evaluating the structural safety and serviceability of new buildings.

Agent	Class	Evaluation Criteria
Wind action	A+	Use of the representative value of the wind speed (w) corresponding to a very rare event (for example, equivalent to an average return period between 1000 and 2500 years) and a design value Qd,w obtained by increasing the legal partial safety coefficient γQ compounded with a multiplicative factor $K_{A+} = 1.1$
	A	Use of the representative value of the wind speed (w) corresponding to the very rare event (for example, equivalent to an average return period between 1000 and 2500 years) and a design value Qd,w obtained by using the legal partial safety factor γQ ($K_A = 1.0$)
	B	Use of the representative value of the legal wind speed (w) (for example, equivalent to an average return period between 500 and 1000 years) and a design value Qd,w obtained by using the legal partial safety factor γQ ($K_B = 1.0$)
Snow action	A+	Use of the characteristic value of the snow load at ground level (s_k) corresponding to a very rare event (for example, equivalent to an average return period of 750 years) and a design value Qd,s obtained by increasing the legal partial safety factor γQ compounded with a multiplicative factor $K_{A+} = 1.1$
	A	Use of the characteristic value of the snow load at Ground level (sk) corresponding to a very rare event (for example, equivalent to an average return period of 750 years) and a design value Qd,s obtained by using the legal partial safety factor γQ ($K_A = 1.0$)
	B	Use of the legal characteristic value of the snow load at ground level (sk) (for example, equivalent to an average return period of 500 years) and a design value Qd,s obtained by using the legal partial safety factor γQ ($K_B = 1.0$)
Seismic action	A+	Use of seismic activity calculation values (A_{Ed}), obtained by using a coefficient of importance γI aggravated by a multiplicative factor $K_{A+} = 1.5$, corresponding to an average return period of approximately 1500 years
	A	Use of seismic activity calculation values (A_{Ed}), obtained by using a coefficient of importance γI aggravated by a multiplicative factor $K_{A+} = 1.25$, corresponding to an average return period of approximately 1000 years
	B	Use of seismic activity calculation values (A_{Ed}), obtained by using the legal coefficient of importance γI (multiplication factor $K_B = 1.0$), corresponding to an average reference period (e.g., 475 years)

These proposals allow designers to systematically make use of metrics (e.g., parameters describing structural loads and structural resistance, amongst others) against which structural performance is to be ranked in accordance with harmonized evaluation criteria (e.g., using an equation that compares these metrics with limiting or acceptable values for applicable engineering parameters) [37]. This provides the basis for performance-based structural design because the proposed evaluation system is applicable to an abstract functional unit that represents the structure of the building without a concrete link to the unique context-specific engineering solution into which this abstract functional unit may be materialized (e.g., concrete structure, steel structures, wood structure, etc.). Designers thus benefit from a mechanism that transforms the performance required for the building structure as an abstract functional unit (i.e., structural performance +, A or B) into a tangible engineering output. In this way, performance-based thinking can be deeply embedded in the design process. In this case, it is a contribution to assuring resilience and reliability concerns against natural risks.

5. Conclusions

Risk-informed performance-based parameters and evaluation criteria can be integrated into performance-based procurement strategies and embedded in design methods, allowing the establishment of differentiated levels of structural safety and serviceability of buildings. In this paper, an in-depth analysis of these strategies is presented for the case of natural risks induced by agents such as wind, snow, earthquake and other natural agents (e.g., floods and temperature variations).

These strategies allow the building owner and/or end-user and the designer to adjust the building structural performance to comply with that specified performance profile.

Author Contributions: Investigation, conceptualization, methodology, funding and draft preparation, N.M.d.A.; editing and validation, M.J.F.S. and F.S.; review, H.R. and D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding aside from the one acknowledged below.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors acknowledge the support of the Civil Engineering Research and Innovation for Sustainability (CERIS) unit hosted by the Department of Civil Engineering, Architecture and Georesources (DECivil) of Instituto Superior Técnico (IST), University of Lisbon (ULisboa) and the funding provided by the Portuguese National Science Foundation thorough grant SFRH/BD/35925/2007. The authors also acknowledge the support of the Slovenian Research Agency and the funding provided by Program No. P5-0018- Decision Support Systems in Digital Business.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Falcão Silva, M.J.; de Almeida, N.M.; Salvado, F.; Rodrigues, H. Modelling Structural Performance and Risk for Enhanced Building Resilience and Reliability. *Innov. Infrastruct. Solut.* **2020**, *5*, 26. [CrossRef]
2. Cerè, G.; Rezgui, Y.; Zhao, W. Critical Review of Existing Built Environment Resilience Frameworks: Directions for Future Research. *Int. J. Disaster Risk Reduct.* **2017**, *25*, 173–189. [CrossRef]
3. Almeida, N.M.D.; Sousa, V.; Dias, L.A.; Branco, F.A. Managing the Technical Risk of Performance-Based Building Structures. *J. Civ. Eng. Manag.* **2015**, *21*, 384–394. [CrossRef]
4. Salvado, F.; de Almeida, N.M.; Vale e Azevedo, A. Toward Improved LCC-Informed Decisions in Building Management. *Built Environ. Proj. Asset Manag.* **2018**, *8*, 114–133. [CrossRef]
5. Almeida, N.; Sousa, V.; Dias, L.A.; Branco, F. A Framework for Combining Risk-Management and Performance-Based Building Approaches. *Build. Res. Inf.* **2010**, *38*, 157–174. [CrossRef]
6. Adedeji, T.J.; Proverbs, D.G.; Xiao, H.; Oladokun, V.O. Towards a Conceptual Framework for Property Level Flood Resilience. *Int. J. SAFE* **2018**, *8*, 493–504. [CrossRef]
7. Cecconi, F.R.; Moretti, N.; Maltese, S.; Dejaco, M.; Kamara, J.; Heidrich, O. Un Rating System per La Resilienza Degli Edifici. *TECHNE J. Technol. Archit. Environ.* **2018**, 358–365. [CrossRef]
8. Burroughs, S. Development of a Tool for Assessing Commercial Building Resilience. *Procedia Eng.* **2017**, *180*, 1034–1043. [CrossRef]
9. Proverbs, D.; Lamond, J. Flood Resilient Construction and Adaptation of Buildings. Available online: https://oxfordre.com/naturalhazardscience/view/10.1093/acrefore/9780199389407.001.0001/acrefore-9780199389407-e-111 (accessed on 19 May 2021).
10. Reckien, D.; Creutzig, F.; Fernandez, B.; Lwasa, S.; Tovar-Restrepo, M.; Mcevoy, D.; Satterthwaite, D. Climate Change, Equity and the Sustainable Development Goals: An Urban Perspective. *Environ. Urban.* **2017**, *29*, 159–182. [CrossRef]
11. Masood, T.; McFarlane, D.; Parlikad, A.K.; Dora, J.; Ellis, A.; Schooling, J. Towards the Future-Proofing of UK Infrastructure. *Infrastruct. Asset Manag.* **2016**, *3*, 28–41. [CrossRef]
12. Almeida, N.; Sousa, V.; Alves Dias, L.M.; Branco, F. General framework for Risk-Managed Performance-Based Building (RM-PBB). In *Proceedings W113 Special Track, 18th CIB World Building Congress*; CIB Publication: Salford, UK, 2010.
13. Hollnagel, E. Resilience Engineering and the Built Environment. *Build. Res. Inf.* **2014**, *42*, 221–228. [CrossRef]
14. Almeida, N. Technical Model of Building Management Performance and Risk Based: Design, Development, and Example of Application to Structures. Ph.D Thesis, IST-ULisboa, Lisbon, Portugal, 2011.
15. Klinke, A.; Renn, O. Precautionary Principle and Discursive Strategies: Classifying and Managing Risks. *J. Risk Res.* **2001**, *4*, 159–173. [CrossRef]
16. Edwards, P.J.; Bowen, P.A. Risk and Risk Management in Construction: A Review and Future Directions for Research. *Eng. Constr. Archit. Manag.* **1998**, *5*, 339–349. [CrossRef]
17. *ISO 6241:1984 Performance Standards in Building—Principles for Their Preparation and Factors to Be Considered*; ISO: Geneva, Switzerland, 2007.
18. El-Sayegh, S.M. Risk Assessment and Allocation in the UAE Construction Industry. *Int. J. Proj. Manag.* **2008**, *26*, 431–438. [CrossRef]
19. Palomo, J.; Insua, D.R.; Ruggeri, F. Modeling External Risks in Project Management. *Risk Anal.* **2007**, *27*, 961–978. [CrossRef]
20. Barber, R.B. Understanding Internally Generated Risks in Projects. *Int. J. Proj. Manag.* **2005**, *23*, 584–590. [CrossRef]

21. Tah, J.H.M.; Carr, V. Information Modelling for a Construction Project Risk Management System. *Eng. Constr. Archit. Manag.* **2000**, *7*, 107–119. [CrossRef]
22. Vanier, D.; Lacasse, M.; Parsons, A. Using Product Models to Represent User Requirements. Construction on the Information Highway. In Proceedings of the CIB Workshop W78, Bled, Slovenia, 10–12 June 1996; pp. 511–524.
23. Kohler, N. From the Design of Green Buildings to Resilience Management of Building Stocks. *Build. Res. Inf.* **2018**, *46*, 578–593. [CrossRef]
24. Wilkinson, S.; Osmond, P. Building Resilience in Urban Settlements. *Int. J. Build. Pathol. Adapt.* **2018**, *36*, 334–336. [CrossRef]
25. Ismail, F.Z.; Halog, A.; Smith, C. How Sustainable Is Disaster Resilience? An Overview of Sustainable Construction Approach in Post-Disaster Housing Reconstruction. *Int. J. Disaster Resil. Built Environ.* **2017**, *8*, 555–572. [CrossRef]
26. Mehmood, A. Of Resilient Places: Planning for Urban Resilience. *Eur. Plan. Stud.* **2016**, *24*, 407–419. [CrossRef]
27. Meacham, B.J. Sustainability and Resiliency Objectives in Performance Building Regulations. *Build. Res. Inf.* **2016**, *44*, 474–489. [CrossRef]
28. Vale, L.J. The Politics of Resilient Cities: Whose Resilience and Whose City? *Build. Res. Inf.* **2014**, *42*, 191–201. [CrossRef]
29. Hassler, U.; Kohler, N. Resilience in the Built Environment. *Build. Res. Inf.* **2014**, *42*, 119–129. [CrossRef]
30. Wholey, F. Building Resilience: A Framework for Assessing and Communicating the Costs and Benefits of Resilient Design Strategies. *Perkins Will Res. J.* **2015**, *7*, 7–18.
31. Francis, R.; Bekera, B. A Metric and Frameworks for Resilience Analysis of Engineered and Infrastructure Systems. *Reliab. Eng. Syst. Saf.* **2014**, *121*, 90–103. [CrossRef]
32. Falcão Silva, M.J.; Almeida, N.; Salvado, F.; Rodrigues, H. *Structural Performance Evaluation System for Improved Building Resilience and Reliability*; CRC/Taylor and Francis Book on Reliability: Abingdon-on-Thames, UK, 2021.
33. Achour, N.; Pantzartzis, E.; Pascale, F.; Price, A.D.F. Integration of Resilience and Sustainability: From Theory to Application. *Int. J. Disaster Resil. Built Environ.* **2015**, *6*, 347–362. [CrossRef]
34. Meacham, B.J.; van Straalen, I.J.J. A Socio-Technical System Framework for Risk-Informed Performance-Based Building Regulation. *Build. Res. Inf.* **2018**, *46*, 444–462. [CrossRef]
35. Roostaie, S.; Nawari, N.; Kibert, C.J. Sustainability and Resilience: A Review of Definitions, Relationships, and Their Integration into a Combined Building Assessment Framework. *Build. Environ.* **2019**, *154*, 132–144. [CrossRef]
36. Saunders, W.S.A.; Becker, J.S. A Discussion of Resilience and Sustainability: Land Use Planning Recovery from the Canterbury Earthquake Sequence, New Zealand. *Int. J. Disaster Risk Reduct.* **2015**, *14*, 73–81. [CrossRef]
37. Almeida, N.M.; Sousa, V.; Dias, L.A.; Branco, F. Engineering Risk Management in Performance-Based Building Environments. *J. Civ. Eng. Manag.* **2015**, *21*, 218–230. [CrossRef]
38. Meacham, B. *Performance-Based Building Regulatory Systems—Principles and Experiences*; A Report of the Inter-Jurisdictional Regulatory Collaboration Committee s.l.; IRCC: Hamilton, ON, Canada, 2010.
39. Spekkink, D. *Performance Based Design of Buildings*; PeBBu Domain 3 Final Report s.l.; CIB: Rotterdam, The Netherlands, 2005.
40. Meacham, B. Performance Based-Building Regulatory System: Structure, Hierarchy and Linkages. *J. Struct. Eng. Soc. N. Z.* **2004**, *17*, 37–51.
41. Lützkendorf, T.; Speer, T. Building Performance or Product Quality: What Information Should Be Signalled in Consumer Markets? In Proceedings of the Toronto: CIB World Building Congress, Toronto, ON, Canada, 2–7 May 2004.
42. *ISO/IEC Guide 67:2004 Conformity Assessment—Fundamentals of Product Certification, ISO Central Secretariat*; ISO: Geneva, Switzerland, 2004.
43. Duncan, J. Performance-Based Building: Lessons from Implementation in New Zealand. *Build. Res. Inf.* **2005**, *33*, 120–127. [CrossRef]
44. *ISO Guide 31:2015 Reference Materials—Contents of Certificates, Labels and Accompanying Documentation, ISO Central Secretariat*; ISO: Geneva, Switzerland, 2015.
45. Olawumi, T.O.; Chan, D.W.M. A Scientometric Review of Global Research on Sustainability and Sustainable Development. *J. Clean. Prod.* **2018**, *183*, 231–250. [CrossRef]
46. Reed, R.; Bilos, A.; Wilkinson, S.; Schulte, K.-W. International Comparison of Sustainable Rating Tools. *J. Sustain. Real Estate* **2009**, *1*, 1–22. [CrossRef]
47. Ling, F.Y.Y.; Hoi, L. Risks Faced by Singapore Firms When Undertaking Construction Projects in India. *Int. J. Proj. Manag.* **2006**, *24*, 261–270. [CrossRef]
48. *ISO/DIS 21929-1:2011 Sustainability in Building Construction—Sustainability Indicators—Part 1: Framework for the Development of Indicators and a Core Set of Indicators for Buildings*; ISO: Geneva, Switzerland, 2011.
49. Decreto-Lei 301/2007, 2007-08-23. Available online: https://dre.pt/pesquisa/-/search/640896/details/maximized (accessed on 18 May 2021).
50. *ISO 15928-1:2015 Houses—Description of Performance—Part 1: Structural Safety*; ISO: Geneva, Switzerland, 2015.
51. *ISO 15928-2:2005 Houses—Description of Performance—Part 2: Structural Serviceability*; ISO: Geneva, Switzerland, 2005.
52. *ISO 15928-3:2015 Houses—Description of Performance—Part 3: Structural Durability*; ISO: Geneva, Switzerland, 2015.
53. Fujitani, H.; Teshigawara, M.; Gojo, W.; Hirano, Y.; Saito, T. Framework for Performance-Based Design of Building Structures. *Comput. Aided Civ. Infrastruct. Eng.* **2005**, *20*, 62–77. [CrossRef]

54. *ISO 11863:2011 Buildings and Building-Related Assets—Functional and User Requirements and Performance in Building—Tools for Assessing and Comparing Functional Performance*; ISO: Geneva, Switzerland, 2011.
55. *EN 1991-1-4:2010 Actions on Structures—Part 1–4: General Actions—Wind Actions*; European Committee for Standardization: Brussels, Belgium, 2010.
56. *EN 1990:2002 Eurocode—Basis of Structural Design*; European Committee for Standardization: Brussels, Belgium, 2002.
57. *ISO 4354:2009 Wind Actions on Structures*; ISO: Geneva, Switzerland, 2009.
58. *ISO 22111:2019 Bases for Design of Structures—General Requirements*; ISO: Geneva, Switzerland, 2019.
59. *ISO 2394:2015 General Principles on Reliability for Structures*; ISO: Geneva, Switzerland, 2015.
60. Holický, M.; Vrouwenvelder, T. Basic Concepts of Structural Reliability. In *Handbook 2—Reliability Backgrounds: Guide to the Basis of Structural Reliability and Risk Engineering Related to Eurocodes, Supplemented by Practical Examples s.l.*; Leonardo Da Vinco Pilot Project CZ/02/B/f/PP-134007; Chapter I. Joint Research Centre Eurocodes; 2005. Available online: https://eurocodes.jrc.ec.europa.eu/showpublication.php?id=63 (accessed on 24 May 2021).
61. *The Housing Quality Assurance Act and Japan Housing Performance Indication Standards*; The Building Center of Japan: Tokyo, Japan, 2005.
62. *EN 1991-1-3:2009 Actions on Structures—Part 1–3: General Actions—Snow Loads*; European Committee for Standardization: Brussels, Belgium, 2009.
63. Formichi, P. EN 1991—Eurocode 1: Actions on Structures—Part 1–3 General Actions—Snow Loads. Eurocodes—Background and Applications. In Proceedings of the Dissemination of Information Workshop, Brussels, Belgium, 18–20 February 2008.
64. *ISO 4355:2013 Bases for Design of Structures—Determination of Snow Loads on Roofs*; ISO: Geneva, Switzerland, 2013.
65. Holický, M.; Marková, J. Reliability Diferentiation. In *Handbook 2—Reliability Backgrounds: Guide to the Basis of Structural Reliability and Risk Engineering Related to Eurocodes, Supplemented by Practical Examples s.l.*; Leonardo Da Vinco Pilot Project CZ/02/B/f/PP-134007; Chapter III. Joint Research Centre Eurocodes; 2005. Available online: https://eurocodes.jrc.ec.europa.eu/showpublication.php?id=63 (accessed on 24 May 2021).
66. *ISO 3010:2017 Basis for Design of Structures—Seismic Actions on Structures*; ISO: Geneva, Switzerland, 2017.
67. *EN 1998-1:2004 Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings*; European Committee for Standardization: Brussels, Belgium, 2004.
68. Solomos, G.; Pinto, A.; Dimova, S. *A Review of the Seismic Hazard Zonation in National Building Codes in the Context of Eurocode 8—Support to the Implementation, Harmonization, and Further Development of the Eurocodes*; JRC Scientific and Technical Reports; European Commission Joint Research Centre: Ispra, Italy, 2008.
69. Fardis, M. *Earthquake-Resistant Design of Concrete Buildings According to EN1998-1 (Eurocode 8)*; European Commission: Brussels, Belgium, 2008.
70. *EN 1991-1-5:2003 Actions on Structures—Part 1–5: General Actions—Thermal Actions*; European Committee for Standardization: Brussels, Belgium, 2003.
71. Holický, M.; Marková, J. *Thermal Actions*; Technical Report; Technical University in Prague: Prague, Czech Republic, 2008.