buildings

Review

Code Requirements for the Seismic Design of Irregular Elevation RC Structures

Davi Santos *, José Melo and Humberto Varum

CONSTRUCT-LESE, Department of Civil Engineering, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal; josemelo@fe.up.pt (J.M.); hvarum@fe.up.pt (H.V.)
* Correspondence: davivs@gmail.com

Abstract: The recent seismic activity highlights the crucial need to enhance seismic design and safety assessment methods, particularly for irregular structures, in both new and existing constructions. The present study focuses on structural irregularities in elevation for buildings, as the design of structural systems involves multiple variables that often result in irregularities in many buildings. This work aims to perform a comparative assessment of the criteria adopted for the evaluation of the structural irregularities in elevation present in European and international seismic codes. This paper is structured as follows: Firtsly, it discusses structural irregularities and more specifically the most common types of structural damage due to seismic events. Then, it shows the documented experiences of structural damages in seismic events associated with structural irregularities in China, Italy, Spain, Nepal and Mexico. Additionaly, it discusses the requirements of the standards on irregularities and their limitation in that matter. At the end of this section, the different approaches of each code in irregularities in elevation are compared. All assessed seismic codes addresses the structural irregularity issue, attributing the desired characteristics of a seismic-resistant structure. However, there are considerable development differences between norms, demonstrated on ambiguity of few codes on criteria of vertical irregulares.

Keywords: structural irregularities; seismic codes; design; buildings

check for updates

Citation: Santos, D.; Melo, J.; Varum, H. Code Requirements for the Seismic Design of Irregular Elevation RC Structures. *Buildings* **2024**, *14*, 1351. https://doi.org/10.3390/buildings14051351

Academic Editor: Harry Far

Received: 29 March 2024
Revised: 23 April 2024
Accepted: 7 May 2024
Published: 9 May 2024

1. Introduction

Building performance during strong earthquakes has been observed and has been used to instruct engineers and builders on how to properly design and construct seismic load-resisting structures [1–5]. In regions characterised by prolonged inhabitation and frequent seismic activity, the refinement of design methodologies has yielded satisfactory structural performance outcomes. Notwithstanding their limited applicability owing to regional differences, the study of these procedures offers valuable insights for structural engineers [6].

Several structural damage mechanisms have been recurrently identified as inappropriate structural configurations, including torsion induced by asymmetrical masonry infills, first soft-storey buildings and deficiencies in reinforcement detailing [7].

Concerning the floor deformation influence on structural behaviour, Ruggieri et al. [8] disclosed that the type of diaphragm notably impacts the likelihood of structural damage. This could also be effective, considering evolution in height, where the deformability reduces on the higher storeys.

Regarding the effect of the irregularity on the demand amplification along the height of the buildings, Ruggieri and Vukobratović [9] concluded that for low-rise buildings, in the perpendicular direction of the analysis, the torsion induces a further acceleration component, which heightened with the floor eccentricity. The results were related to the floor eccentricity, the elevation of the considered node and, regarding the nonlinear field, the ductility and the yielding force became significant. Similar results have been taken from ref. [10].

Despite extensive research endeavours dedicated to assessing the seismic behaviour of asymmetric structures, relatively less effort has been undertaken toward the various types of irregular structures [11]. This study emphasised the reduced research focusing on structures exhibiting irregularities along both principal directions. Some authors suggest that the implementation and adherence to seismic design codes are crucial factors in mitigating earthquake community risk [12]. Further research is required on soil movements, the deterioration of the material properties, the efficacy of the shear walls positioning and many other related issues to perform a better seismic risk assessment.

In the paper, the following seismic codes were assessed:

1. EN 1998-1:2005 (Europe);
2. prEN 1998-1-2:2024 (Europe);
3. NBR 15421:2023 (Brazil);
4. NTC-RSEE from Mexico City (Mexico);
5. Manual de diseño obras civiles: diseño por sismo (Mexico);
6. ASCE/SEI7-22—minimum design loads for buildings and other structures (USA);
7. Diseño sísmico de edifícios (NCh 433) (Chile);
8. NZS 1170-5 structural design actions (New Zealand).

Regarding the irregularity in elevation criteria, it was referenced quantitatively, qualitatively or not referenced on each seismic code. The following criteria are considered in the seismic codes comparisons:

1. Continuity of structural elements;
2. Variation of lateral stiffness;
3. Existence of weak floors (soft storey);
4. Mass variation;
5. Ratio between actual and required resistance;
6. Geometry criteria;
7. Resistance variation (weak storey);
8. Storey area variation;
9. Ratio between elevation and smallest dimension in plan.

2. Structural Irregularities in Elevation

A proper structural conception is essential to ensure optimal performance under any loading conditions. Regular structures with redundant resistant systems for horizontal loading demands typically exhibit better behaviour. Conversely, complex structural systems often present deficiencies in the dimensions and detailing of structural elements [6].

Over the past decade, numerous researchers have worked on the seismic vulnerability analysis of irregular building structures. Mouhine and Hilali [13] scrutinised the seismic vulnerability of building structures characterised by vertical geometric irregularities positioned at various heights along the buildings. Their findings underscored the significant impact of setback percentage and its placement on both the performance and lateral stiffness of these structures. Setback causes the non-uniform distribution of mass and stiffness in the vertical direction, which may have a significant influence on seismic response [14].

Similarly, Ruggieri and Uva [15] conducted a study focusing on the performance evaluation of eight low-rise reinforced concrete building structures, of which seven featured in-plane irregularities. Using pushover analysis, they highlighted the influence of seismic motion spatial variability on the structural seismic behaviour. Furthermore, Men et al. [16] explored the seismic vulnerability of RC structures exhibiting vertical irregularities. Their research emphasised the interplay between seismic intensity, structural performance levels and the vulnerability of such structures.

Irregularities in elevation can affect different characteristics of the structural system, such as stiffness, mass and strength. These can come from a variety of sources, including the following:

1. Stiffness irregularity—soft storey: Checked when there are variations of stiffness from one floor to another, resulting in a weak floor, which may give rise to mechanisms such as soft storey [17]. The lateral stiffness of buildings is also strongly affected by the presence of setbacks [13,18,19].
2. Strength irregularities—weak storey:
   i. Due to the existence of different heights of the constituent parts of the building and different heights between buildings: occur when adjacent buildings have different heights, resulting in restrictions on the movements of the lower floors [20].
   ii. Irregularities in the bearing capacity of a floor: due to the different resistance of the elements that support the action seismic activity in a direction on a given floor, in relation to the next floor [21].
   iii. Irregularities due to discontinuities in the load paths: verified with the absence of continuity of the resistant elements from one floor to the next [22].
3. Mass irregularities: Checked when the mass of a floor is much higher or lower than the others. An example of a practical aspect of this situation is the need for floor technicians with heavy machinery [21].

Vertical irregularity is characterised by abrupt shifts in mass, stiffness and strength along the height, leading to soft/weak storey behaviour. These storeys are susceptible to an earlier collapse by concentration in element forces and ductility demands [23]. However, these discontinuities, treated by current seismic codes as vertical irregularities, undoubtedly do not lead to increases in plastic demands and poor seismic performance [24,25].

The most common type of possible damages due to seismic events, based on the published work about this matter, are listed below [6]:

1. Stirrups and hoops: These stem from inadequate detailing, insufficiency or absence of transverse reinforcement, poor detailing of hoops and wide spacing between stirrups.
2. Longitudinal reinforcement detailing (bond, anchorage and lap splices): Smooth bars reduce the strength capacity of RC elements. Significant deterioration of the bond conditions is observed along the longitudinal bars, exceeding and deviating the plane sections theory.
3. Shear and flexural capacity of elements.
4. Inadequate shear capacity of structural joints.
5. Strong-beam weak-column mechanism.
6. Short-column mechanism.
7. Irregularities in plan and/or in elevation.
8. Pounding.
9. Damages in secondary elements.
10. Damages in non-structural elements.

Furthermore, in the conclusions of the published work about the assessment of modern seismic codes about the structural efficiency in earthquake events by Athanatopoulou and Manoukas [26], it is highlighted:

1. Torsional sensitivity of a building is avoided only if a minimum torsional radius is ensured. However, this condition does not imply that adequate static torsional stiffness is available either.
2. In general, displacement or drift ratios are not reliable either as torsional sensitivity criteria or as a measure of displacement amplification at the perimeter of buildings. Therefore, a revision of the relevant code provisions should be examined.

It is necessary for a constant assessment and update of seismic codes to ensure structural safety during those events.

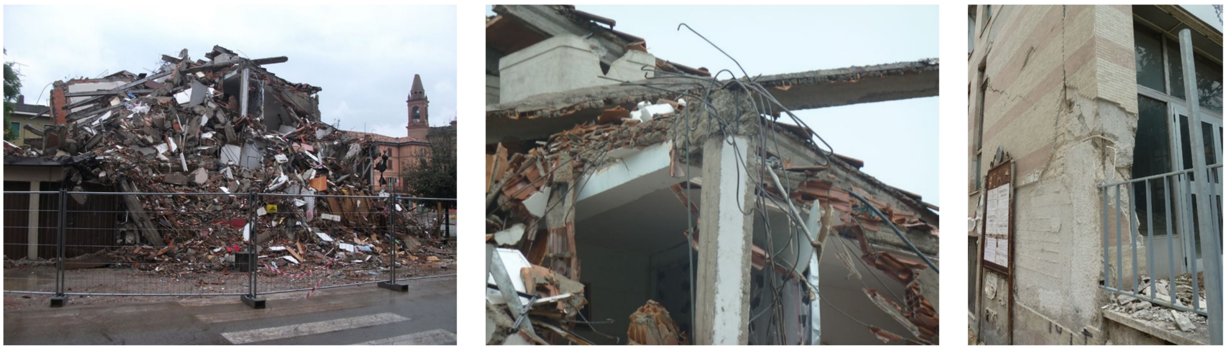
3. Damages Associated with Structural Irregularities

The seismic behaviour of RC structures is closely tied to the characteristics of their structural elements, including stiffness, ductility, strength and energy dissipation capacity.

The overall strength is a result of the combined effort of individual structural components and their interactions. Properly designing and detailing the connections between these elements is crucial, as inadequate transverse reinforcement has led to various failures, both at local and global scales. In the case of structures with substantial redundancy, their seismic performance hinges on their ability to redistribute loads effectively [27].

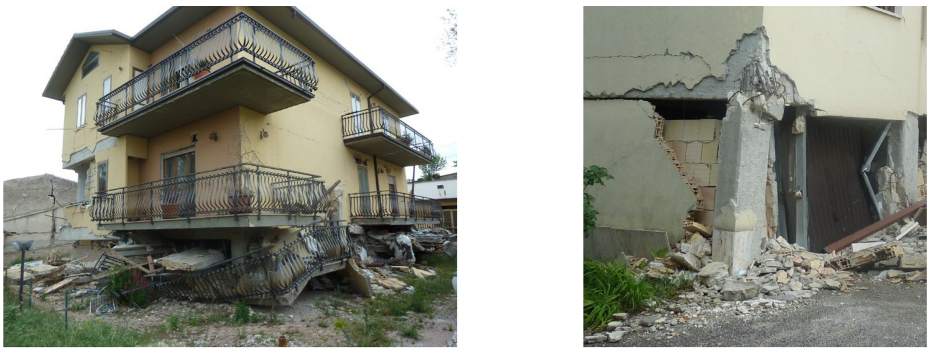
The detailing of the RC elements stands out as a prevalent cause of damage documented in recent seismic events. The confinement effect from the transverse reinforcement, related to the spacing and diameter of the stirrups, longitudinal reinforcement arrangement and quality of the steel employed, is crucial in preventing concrete detachment. Based on the observations made in situ, especially on Sichuan (China) [28–31], L'Aquila (Italy) [3,32], Lorca (Spain) [33], Emilia (Italy) [34–36], Gorkha (Nepal) [37–39], Puebla (Mexico) [5,40] and Eastern Anatolia region (Turkey) [4], it can be inferred that this approach was not implemented in buildings constructed during earlier decades.

Another common type of damage noticed in recent earthquakes is related to insufficient shear capacity of RC elements. The shear strength limit is before the onset of yielding, indicating a constraint on energy dissipation. Generally, corner columns encounter challenges associated with their shear strength capability and inadequate confinement, particularly when the building's structure features disparities between its mass and stiffness centres. Figures 1–3 present examples of structural damages due to seismic events.



(**a**) (**b**) (**c**)

Figure 1. Emilia, Italy—2012: (**a**) RC structure collapsed in Cavezzo; (**b**) inadequate reinforcement joint detail; (**c**) damage of columns due to inadequate detailing for confinement.

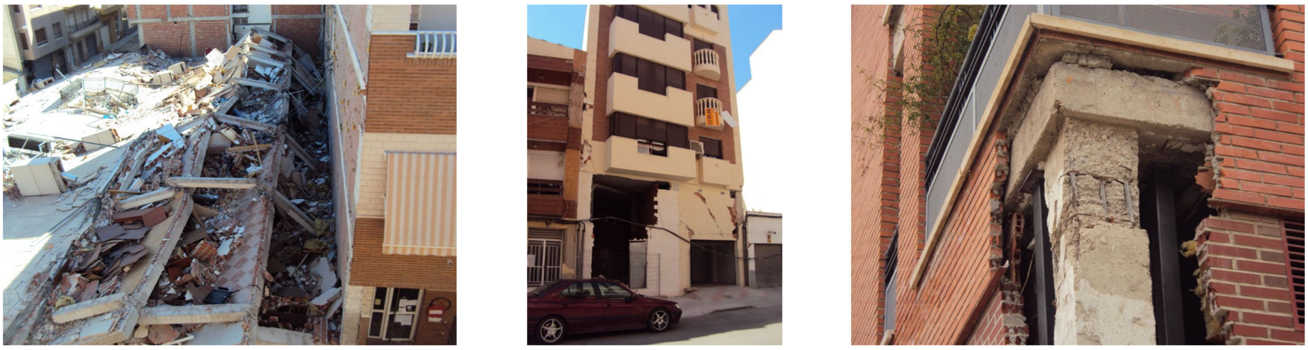


(**a**) (**b**)

Figure 2. L'Aquila, Italy—2009: (**a**) damages on RC structure in L'Aquila; (**b**) node damage of reinforced concrete elements.

Ductile behaviour should be the premise of the seismic design of columns and beams. This strategy involves a potential reduction in demand within the compression zone and/or enhancing capacity. This can involve restricting axial loading, enlarging cross-sectional areas or controlling tensile reinforcement while balancing forces with compression loads.

Furthermore, strengthening the compression region can be achieved by employing higher-quality concrete and effective confinement [27].



(**a**) (**b**) (**c**)

Figure 3. Lorca, Spain—2011: (**a**) building collapse after the earthquake; (**b**) building with a soft-storey mechanism; (**c**) column failure due to inadequate detailing of the transverse reinforcement.

Among the paramount concerns regarding the seismic behaviour of RC structures is the interaction of the masonry infill walls with the structural components. These infill walls can alter the lateral stiffness, strength, ductility and energy dissipation capacity of buildings. As a result, changes in the natural frequencies of the building and its corresponding vibration mode may occur, leading to seismic action surpassing the anticipated levels of the design. This phenomenon can elevate the seismic vulnerability of the buildings.

The distribution of infill walls, typically determined by the architectural team, can significantly influence the global seismic performance of a building, notably when the building is irregular in height and/or in plan. Considerable local failures have been documented in the seismic performance of masonry infill walls, attributed to in-plane, out-of-plane and combined seismic loadings.

4. Discussion and Limitation of Code Requirements on Irregularities

4.1. EN 1998-1:2005—Europe

Building structures are classified by Eurocode 8 [41] as regular and non-regular, in plan and in elevation. This distinction has implications for the following aspects of seismic design, as demonstrated in Table 4.1 of Eurocode 8 [41]:

1. The structural model: a planar model or a spatial model;
2. The method of analysis: response spectrum analysis or a modal analysis;
3. The value of the behaviour factor "q" must be reduced by 20% for buildings that are not regular in elevation and it also reduces the presence of irregularities in plan, depending on the structural system and the ductility class, as explained in 5.2.2.2 (6) of Eurocode 8 [41].

A building classified as regular in elevation must satisfy all the conditions indicated in the following paragraphs [41]:

1. All systems resistant to lateral actions, such as cores, load-bearing walls or frames, are continuous from the foundation to the top of the building, or, if there are floor setbacks at different heights, to the top of the area considered in the building.
2. The lateral stiffness and the mass of each floor remain constant or show a gradual reduction, without abrupt changes, from the base to the top of the considered building.
3. In buildings with a frame structure, the ratio between the actual floor strength and the strength required by the design must not vary disproportionately between adjacent floors. In this context, the particular aspects of frame structures with masonry infills are dealt with in 4.3.6.3.2 of this code.
4. When the building has setbacks, the following additional conditions must be applied:

i. In the case of successive setbacks that maintain an axial symmetry, the setback on any floor must not exceed 20% of the plan dimension of the lower level in the direction of the setback.
ii. In the case of a single setback placed in the lower 15% of the overall height of the primary structural system, it must not exceed 50% of the plan dimension of the lower level. In this case, the structure of the lower area located inside the vertical projection of the upper floors must be calculated to resist at least 75% of the horizontal force that would act at that level in a similar building without widening the base.
iii. In the case of non-symmetrical setbacks, the sum, on each side of the setbacks of all floors, must not exceed 30% of the dimension in plan at floor level above the foundation or above the upper level of a rigid basement, and each setback must not be more than 10% of the dimension in plan of the lower level.

The European standard presents three levels of detailing of concrete structures depending on the actions applied: DCL, DCM and DCH levels (low, medium and high capacity to dissipate energy, respectively) [41]. When there is no DCL detail specification, Eurocode 2 [42] recommendations are used.

4.2. prEN 1998-1-2:2024—Europe

The second generation of Eurocode 8 is currently ongoing to improve and update the regulation. Among the changes, such as restructuring the standard and increasing content relevant to the topic, this topic aims to analysethe differences regarding the treatment of irregularities between the two versions, the current one and its draft version (draft).

The prEn 1998-1-2:2024 [43], like the current version, maintains the same classification of each unit regardless of the regular and irregular structures. The criteria for regularity in elevation present some changes which stand out, as follows:

1. As for the lateral stiffness and the mass of each floor, while in the current version, these factors remain constant or have small gradual reductions in height (without specifying a percentage), in the draft version, these reductions should not exceed, respectively, 30% and 150% in relation to the floor bottom, without sudden changes from consecutive storeys. In the case of mass, that difference is considered until one storey below the top storey.
2. Regarding the ratio between the real strength of the floor and that required for calculation, in the current version, it is said that this ratio should not vary disproportionately (but without setting a proportion) between the floors of framed structures, whereas in the draft version, it states that this ratio must not exceed 30% and does not refer only to framed structures.
3. The current version addresses the presence of setbacks and characterises additional conditions in the treatment of buildings, whereas the version under study also includes such a requirement.

4.3. NBR 15421:2023—Projeto de Estruturas Resistentes a Sismos—Procedimento—Brazil

This code defines seismic categories exclusively in terms of their seismic zones, as shown in 7.3. These categories are used to establish the allowed seismic-resistant structural systems, the limitations on irregularities of the structures, the components of the structure that must be designed in terms of seismic resistance and the types of seismic analysis (methods of calculation) that can be adopted [44].

This code allows the use of three calculation methods for seismic analysis: the method of equivalent horizontal forces (for seismic categories A, B and C), the spectral method (for seismic categories B and C observing the limitation of pavements and structural irregularities) and the method of historical accelerations in time (for seismic categories B and C for seismic categories B and C observing the limitation of pavements and structural irregularities) [44].

Building structures are classified by NBR 15421 [44] as regular and non-regular, in plan and in elevation. Structures showing one or more of the irregularities types listed below must be designed as having structural irregularities in elevation [44]:

1. Type 4: Discontinuities in the vertical seismic resistance path, such as consecutive vertical resistance elements in the same plane but with axes greater than their length apart, or when resistance between consecutive elements is greater in the upper element.
2. Type 5: Characterisation of an "extremely weak pavement" as one in which its lateral resistance is less than 65% of the resistance of the pavement immediately above. The lateral resistance is computed as the total resistance of all earthquake-resistant elements present in the considered direction. In case the seismic forces are not multiplied by the over-resistance coefficient Ω_0, structures cannot be more than two stories and not more than 9 m of elevation.

It addresses that columns, beams, slabs and trusses supporting porticos and seismic-resistant wall columns that present Type 2 or Type 4 irregularity should be designed considering the seismic effects in the vertical direction (E_v) and the consequences of the horizontal earthquake with the effect of over resistance (E_{mh}), according to 8.4 of this code [44]. If the structure presents structural irregularity in plan types 1, 2 or 3, a three-dimensional model should be used. In this model, each node must have at least three degrees of freedom, two translations in a horizontal plane and one rotation around a vertical axis [44]. Also, in the case of seismic category C structures, in which there is a structural irregularity in plan type 1, the accidental torsional moments M_{ta} at each elevation should be multiplied by the torsional amplification factor A_x [44].

This code does not deal with the structural detailing drawing of structures subjected to seismic actions, leaving all discussion about the structural detail drawing for Code NBR 6118 [45], which does not specifically address the matter considering seismic actions. This is a limitation of those codes regarding seismic actions on structural detailing matter when compared, for instance, with Eurocode 8.

4.4. NTC-RSEE from Mexico City—Mexico

The Mexican code from the Public Administration of Mexico City classifies the building structures as regular, irregular and strongly irregular, without distinction in criteria of irregularity in plan and in elevation. A structure is classified as regular when it satisfies the requirements indicated below [46]:

1. The different walls, frames and other earthquake-resistant vertical systems are visibly parallel to the main orthogonal axes of the building. An earthquake-resistant plane or element shall be visibly parallel to one of the orthogonal axes when the angle it forms in plan with the axis in question does not exceed 15 degrees.
2. The ratio between its height and its smallest size in plan is not greater than 4.
3. The ratio of length to width in plan is no more than 4.
4. In plan has no setbacks or projections of dimensions greater than 20% of the dimension in plan measured parallel to the direction in which the setback or projection is considered.
5. Each level has a floor system whose rigidity and strength in its plan satisfy the requirements for a rigid diaphragm.
6. The floor system has no openings that, at some level, exceed 20% of its flat area on that level, and the empty areas do not differ in position from one floor to another. This requirement does not apply to the roof.
7. The weight of each level, including the overload that must be considered for the seismic project, is not greater than 120% of that corresponding to the floor immediately below.
8. In each direction, no floor has a floor dimension greater than 110% of the dimension of the floor immediately below. In addition, no floor has a floor dimension greater than 125% of the smallest of the lower floor dimensions in the same direction.

9. All columns are restricted on all floors in both directions of analysis by horizontal diaphragms or by beams. Consequently, no column passes through a floor without being attached to it.
10. All the columns of each floor have the same height, although it can vary from one floor to another. Except for this item, the top floor of the building.
11. The lateral stiffness of no floor differs by more than 20% from that immediately below. Except for this item, the top floor.
12. On no floor does the lateral displacement of any point on the floor exceed the average lateral displacement of the floor ends by more than 20%.
13. In systems designed for "Q" (coefficient of seismic behaviour) equal to 4, the ratio of lateral strength and design action shall be higher than 85% of the average of these ratios for all floors. In systems designed for "Q" equal to or less than 3, on no floor shall the ratio indicated above be less than 75% of the average of these ratios for all floors. To verify compliance with this requirement, the resistance capacity of each floor will be calculated considering all the elements that can contribute significantly to it. The top floor is excluded from this requirement.

A structure is classified as irregular when it does not satisfy one of the requirements "5", "6", "9", "10", "11", "12" and "13" or does not satisfy two or more of the requirements "1", "2", "3", "4", "7" and "8", as listed above. A structure is considered strongly irregular if it does not meet two or more of the requirements "5", "6", "9", "10", "11", "12" and "13" listed above, or if any of the following conditions are met:

- The lateral displacement of any point of one of the plants exceeds by more than 30% of the average of the displacements of the extremities.
- The lateral stiffness or shear strength of any floor exceeds that of the floor immediately below by more than 40%. To verify compliance with this requirement, the strength and lateral stiffness of each floor will be calculated considering all the elements that can contribute significantly to them.

More than 30% of the columns located on one floor do not meet requirement "9" listed above.

4.5. Manual de Diseño Obras Civiles: Diseño por Sismo—Mexico

The code developed by the Mexican Federal Electricity Commission (CFE) classifies the building structures as regular, irregular and strongly irregular, without distinction in criteria of irregularity in plan and in elevation. A structure is classified as irregular when it does not satisfy three of the requirements indicated below [47]:

1. The distribution in plan of the mass, walls and other resistant elements of the building must be symmetrical with respect to two orthogonal axes.
2. The ratio of elevation and smallest dimension in plan cannot be greater than 2.5.
3. The ratio between the length and width of the base cannot exceed 2.5.
4. Existing setbacks and overhangs cannot exceed 20% of the dimension in plan, measured parallel to the direction in which the setback or overhang is located.
5. On each floor, there must be a rigid diaphragm behaviour.
6. There cannot be any opening in the slab that exceeds 20% of the dimension in plan, measured parallel to the opening. Hollow zones must not appear staggered between adjacent floors and the total opening area must not exceed 20% of the floor area.
7. The mass of each floor cannot exceed 110% of the corresponding floor immediately below, except for the top floor, nor may it be less than 70% of the mass of the floor immediately below. The top floor is exempt from this condition.
8. No floor may have an area greater than 110% nor less than 70% of the floor area immediately below.
9. All columns are restricted by floors, in orthogonal directions, by horizontal diaphragms.
10. Stiffness cannot differ between floors by more than 50% from that of the floor immediately below.

11. On no floor can the statically calculated torsional eccentricity exceed 10% of the plan dimension of that floor, measured parallel to the mentioned eccentricity.

It can also be classified as strongly irregular if it meets any of the following requirements [47]:

1. The statically calculated torsional eccentricity exceeds 20% of the floor plan dimension measured parallel to the mentioned eccentricity.
2. The rigidity or shear resistance of the tread exceeds more than 100% that of the tread immediately below.
3. At the same time, fulfill the conditions "10" and "11" described above.
4. Does not fulfill four or more regularity conditions described above.

For seismic analysis of building structures, three types of methods can be used [47]: a simplified method, a static method and a dynamic method. The simplified method is simpler to use. However, it is only applicable to regular structures that meet all the requirements indicated by the method. The static method is more suitable for regular structures with height conditioned by the type of terrain where they are inserted. The dynamic method can be used on any structure, regardless of its characteristics.

According to the code [47], the structure must be analysed under seismic action considered in two independent orthogonal directions. As a combination of the effects of seismic action in two orthogonal directions, the standard proposes that the value of the action in each direction is increased by 30% of the value of the corresponding orthogonal direction.

4.6. ASCE/SEI7-22—Minimum Design Loads for Buildings and Other Structures—USA

The American regulation [48] classifies structures as regular or irregular in elevation according to a set of criteria related to the structural configurations of the building that result in a classification divided by types.

This code also divides types according to a Seismic Project Category, which is a classification assigned to a structure based on its occupation category and the seismicity of that area. Where, as indicated on the (ISAT) web pages, the category assignment can vary from A-F and can be defined as follows:

1. Seismic category A: it corresponds to buildings located in areas where little seismic activity is expected and with good soil;
2. Seismic category B: it corresponds to buildings belonging to occupation type I, II or III where seismic activity is expected to be moderate, located on stratified soil consisting of good and bad soils;
3. Seismic category C: it corresponds to buildings belonging to occupation type IV where seismic activity is expected to be moderate, or buildings belonging to occupation type I, II or III where seismic activity is expected to be more severe;
4. Seismic Category D: it corresponds to buildings located in areas where they are expected to experience severe and destructive seismic action, but not located close to a major fault;
5. Seismic category E: it corresponds to buildings belonging to occupation type I, II or III located a short distance from large active faults;
6. Seismic category F: it corresponds to buildings belonging to occupation type IV located a short distance from major active faults.

Further, the type of occupation can be defined as follows:

1. Type of occupancy I: buildings that pose a small risk to human life in the event of failure;
2. Type of occupancy II: buildings that do not fit into any of the other types of occupancy.
3. Type of occupancy III: buildings that pose a substantial risk to human life and in the event of failure;
4. Type of occupation IV: buildings considered essential for human life.

To classify structures as regular or irregular in elevation, ASCE/SEI7-22 [48] defines structures as follows:

1. Type 1a—Stiffness–soft storey irregularity: it exists where there is a floor in which the lateral stiffness is below 70% of that in the storey above or below 80% of the mean stiffness of the three floors above;
2. Type 1b—Stiffness–extreme soft storey irregularity: it exists where there is a floor in which the lateral stiffness is below 60% of that in the storey above or below 70% of the average stiffness of the three floors above;
3. Type 2—Vertical geometric irregularity: it exists where the horizontal dimension of the seismic force-resisting system in any floor exceeds 130% of that in an adjacent storey;
4. Type 3—In-plane discontinuity in vertical lateral force-resisting element irregularity: it occurs where there is an in-plane offset of a vertical seismic force-resisting element, leading to overturning demands on supporting structural elements;
5. Type 4a—Discontinuity in lateral strength–weak storey irregularity: it occurs where the storey lateral strength is below 80% of that in the floor above;
6. Type 4b—Discontinuity in lateral strength extreme weak storey irregularity: it occurs where the storey lateral strength is below 65% of that in the storey above.

This code [48] also provides two exceptions on vertical structural irregularities of types 1a, 1b and 2 listed below:

1. They do not apply where no storey drift ratio, regarding design lateral seismic force, is higher than 130% of the next floor above the storey drift ratio. Torsional effects are excluded from the computation of storey drifts. Assessment of the storey drift ratio for the upper two storeys is unnecessary.
2. These considerations are not mandatory for single-storey buildings in any Seismic Design Category nor for two-storey buildings categorised under Seismic Design Categories B, C or D.

Furthermore, this code provides constraints and additional requirements for systems with structural irregularities:

1. Prohibited vertical irregularities for seismic design categories D through F: Structures designated under Seismic Design Category E or F with vertical irregularities Type 1b, 4a, 4b or Seismic Design Category D structures with irregularity in elevation Type 4b are not allowed. However, it is permitted if the E and F Seismic Design Category structures present irregularity in elevation Type 4a where the storey lateral strength is not less than 80% of the floor above.
2. Extreme weak storeys: Structures featuring a vertical irregularity Type 4b must not exceed 2 storeys or 9 m in structural height. However, this limit does not apply if the "weak" storey can resist a total seismic force equivalent to Ω_0 times the design force.
3. Elements supporting discontinuous walls or frames: Structural elements carrying discontinuous walls or structural frames with horizontal and/or vertical irregularity Type 4 must be designed to resist the seismic load effects, considering overstrength. The connections of these elements to the supporting members must be sufficient to transmit the forces for which they were designed.
4. Increase in forces as a consequence of irregularities for seismic design categories D through F: For structures categorised under Seismic Design Category D, E or F and presenting a horizontal structural irregularity of Type 1a, 1b, 2, 3 or 4 or a vertical structural irregularity of Type 3, the design forces for some components of the seismic force-resisting system, such as connections of diaphragms to vertical elements and collector and connection to vertical elements, must be increased 25%.

Forces calculated using the seismic load effects, including overstrength, do not require augmentation.

This code [48] allows structures to be analysed using several methods. However, the model must incorporate the stiffness and strength characteristics of components that are significant to forces and deformation distributions within the structure. It also has to represent the spatial distribution of mass and stiffness throughout the structure. Additionally, it should consider, for RC structures, the stiffness properties of concrete and masonry elements regarding the effects of cracked sections.

4.7. Diseño Sísmico de Edifícios (NCh 433)—Chile

The seismic assessment in Chilean standards is provided by the following:

1. NCh 433:1996 [49], modified in 2012—Diseño sísmico de edifícios;
2. NCh 2369:2003 [50]—Diseño sísmico de estructuras e instalaciones industriales;
3. NCh 2745: 2013 [51]—Análisis y diseño de edificios con aislación sísmica;
4. NCh 3411: 2017 [52]—Diseño sísmico de edificios con sistemas pasivos de disipación de energia;
5. NCh 3357:2015 [53]—Diseño sísmico de componentes y sistemas no estructurales.

The Chilean code NCh 433 does not explicitly address structural irregularities. It only mentions that irregular buildings can only be designed as a single structure when the diaphragms are calculated and built so that the structure behaves during earthquakes as a single one. This code suggests a separation of the building into regular parts (INN 2012).

This code also highlights two things [49]:

1. If an irregular building in plan is designed as a single structure, special care must be taken in dimensioning the connections between the different parts that make up the floor.
2. In floors where there is rigidity discontinuity in the resistant planes or other vertical substructures, it must be verified that the diaphragm is able to redistribute forces.

Regarding structural analysis methods, the code allows a static analysis or a spectral modal analysis, depending on certain geometric conditions of the structure [49]. It presents two response modification factors, one for equivalent static analysis (R) and another for spectral analysis (R_0). This factor reflects the energy absorption and dissipation characteristics of the resistant structure, as well as the experience in the seismic behaviour of the different types of structures and materials used.

4.8. NZS 1170.5 Structural Design Actions—New Zealand

The New Zealand Code addresses structural irregularity and encourages structural designers to design regular structures due to seismic behaviour. Any structure is considered irregular as long as it meets one of the irregularity criteria present in the code. Single-storey houses or roofs weighing less than 10% of the level below will not be considered when applying these criteria [54].

A structure might be considered irregular in elevation if, according to the New Zealand Code [50]:

1. One floor significantly exceeds the height of adjoining storeys, leading to a reduction in stiffness;
2. The ratio of mass to stiffness in adjoining storeys differs significantly;
3. The smaller dimension was below the larger dimension, resulting in an inverted pyramid effect;
4. The structure presents, at one or more levels, substantial horizontal offsets in the vertical elements of the horizontal force-resisting system, even though the structure has a symmetrical geometry about the vertical axis.
5. The structure exhibits abrupt changes in strength capacity between storeys, resulting in the concentration of energy demand in the resisting elements of a specific storey.

The method of seismic analysis is conditioned by the presence of irregularities and the method of equivalent forces is indicated only for regular structures that comply with certain conditions. For irregular structures, the modal response spectrum method or historical accelerations in time is used.

4.9. Comparative Analyses of the Studied Codes

Table 1 presents a summary of the regularity criteria in elevation addressed by the analysed codes. Table 2 presents the reduction of the behaviour coefficient due to irregularities considered in each code standard studied.

Table 1. Synthesis of regularity criteria in elevation.

Criteria	Europe	Europe (Draft)	Brazil	Mexico NTC-RSEE	Mexico CFE	USA	Chile	New Zealand
Continuity of structural elements	R	R	R	N	N	R	N	N
Variation of lateral stiffness	R	Q	Q	Q	Q	Q	N	Q
Existence of weak floors (soft storey)	N	N	Q	N	N	Q	N	N
Mass variation	R	Q	N	Q	Q	N	N	Q
Ratio between actual and required resistance	Q	Q	N	N	N	N	N	N
Geometry criteria	Q	R	N	Q	Q	Q	N	Q
Resistance variation (weak storey)	N	N	R	N	Q	Q	N	Q
Storey area variation	N	N	N	Q	Q	N	N	N
Ratio between elevation and smallest dimension in plan	N	N	N	Q	Q	N	N	N

N: no reference; R: referenced, but without quantification criteria; Q: presents quantification criteria.

Table 2. Expected reduction in the behaviour coefficient (q)/structural response modification coefficient (R-factor) due to irregularity in elevation.

Region	Coefficient/R-Factor
Europe	A 20% reduction in the presence of irregularities in elevation. Reduction in the presence of irregularities in the plan, depending on the structural system and of the ductility class, as explained in 5.2.2.2 (6) of this standard. With this reduction, the structure must be further strengthened. It can be at the level of the geometry of the elements and/or the amount of reinforcement.
Brazil	R-factor is mentioned, but no reductions in the presence of irregularities are numerically determined.
Mexico (NTC-RSEE)	Seismic behaviour factor Q is mentioned. A 20% reduction in the presence of irregularities. A 30% reduction for heavily irregular structures.
Mexico (CEF)	Seismic factor Q is mentioned. Reduction of 10% when the regularity requirements listed from "a" to "i" are not met. Reduction of 20% when two or more regularity requirements are not met and/or the regularity requirements "j" or "k" are not met. A 30% reduction when the structure is classified as strongly irregular.
USA	The redundancy factor ρ can be 1,0 or 1,3 for the structures in the category of irregularity D through F. This factor reduces the response modification coefficient, R, for less redundant structures.

Table 2. *Cont.*

Region	Coefficient/R-Factor
Chile	R-factor is mentioned, but no reductions in the presence of irregularities are numerically determined. Topic 5.5.2.2, however, specifically states that structures with irregularities in plan only can be designed as a single structure when the rigid diaphragm is guaranteed, according to topic 5.5.2.1 of this code. Otherwise, each part should be designed separately, according to topic 5.10 of this code.
New Zealand	The structural performance factor and structural ductility factor are mentioned, but no reductions in the presence of irregularities are numerically determined.

These comparative assessments of those codes relative to elevation regularity criteria led to the following conclusions:

1. The importance given to the mass variation and stiffness in elevation is notorious, as practically all standards contemplate this type of criterion.
2. There are different procedures to verify the criteria of variation of stiffness elevation: some codes make this verification based on the stiffness of the vertical elements on each floor, others through the relationship of the drift between successive floors and, for the latter, there is a need for a previous model.
3. The Chilean code does not address any reference or quantification methods to all regularity criteria in elevation.
4. The European code is the only one that requires that the actual resistance is proportional to the required resistance and that these do not differ too much, which is a difficult criterion to verify.
5. The Mexican code presents two specific criteria which do not appear in the other analysed codes: storey area variation and the ratio between elevation and smallest dimension in plan.

Numerous studies indicate that all the codes that discuss that matter limit themselves from classifying certain common irregularities, suggesting the permissible extent of those typical cases. Nevertheless, it is essential to explore the nature of the high seismic vulnerability to enhance their structural behaviour during seismic events [11].

The EC8 is the most demanding standard because it is not enough to meet one of the regularity criteria for the coefficient of behaviour to be affected. In other codes, the correction of the behaviour coefficient depends on the type of criterion that is violated.

The EC8, the American and Mexican standards adopt the reduction of the coefficient of behaviour or R-Factor in irregular buildings, ranging between 20% and 30%. The biggest penalty comes in the Mexican code, which can reach 30% in cases of heavily irregular structures.

New Zealand and Brazilian standards have some quantified criteria for regularity in plan and elevation. However, these do not lead to any reduction in the coefficient of behaviour or R-Factor. The Chilean standard has no restrictions on buildings with structural irregularities. In these cases, structural irregularities only have implications for seismic analysis methodology.

When the structure is regular in plan and in elevation, all standards allow a seismic analysis to be carried out by the method of equivalent forces. Differences arise when the structure is classified as irregular, either in plan or in elevation, or both, in which a modal dynamic analysis is predominantly suggested.

Not all the analysed seismic codes present the same degree of development and approach to the theme. However, the first conclusion that can be drawn from the analysis is that all seismic standards address the theme of structural irregularities. However, Chile's standard is the only one that does not have well-established criteria for irregularities. In addition, some norms become confusing, making it difficult to understand what is affected by the existence of irregularities. In addition, although there is a set of criteria that are repeated in different standards, the limits allowed are not always the same in the different standards since these are related to the seismic activity to which the country may be subject.

5. Conclusions

The standards indicate a consensus regarding the desired characteristics of a seismic-resistant structure, which include simplicity, symmetry, uniformity and redundancies. However, a comparative analysis conducted in this study has revealed significant variations in the representation of seismic hazard.

Eurocode 8 sets out certain criteria that do not involve processes to quantify their influence, which may excessively penalisethe final classification for regularity in elevation and in plan and reduce the maximum permissible coefficient of behaviour. It is important to note that the new version of Eurocode 8 provides quantification of some irregularity criteria and clarifies the calculation procedures to address these irregularities.

The draft version of the second generation of Eurocode 8 includes proposed changes that address certain challenges and issues highlighted by the designers. Specifically, the changes aim to mitigate potential errors arising from varied interpretations by introducing quantification for some regularity criteria and verification limits. However, the application and interpretation of these criteria are subject to the designer's sensitivity to the problem, level of experience and knowledge, which may affect the resulting outcomes.

The Mexican codes and the American codes are as strict as Eurocode 8, although they have some differences in the assessments of some irregularity criteria. Both countries are quite traditional in the field of study of seismic engineering, a factor evidenced by the evolution of their standards.

The standards of New Zealand and Brazil incorporate specific criteria to assess regularity in plan and elevation of structures. However, these criteria do not result in any reduction in the coefficient of behaviour or R-Factor. On the other hand, the Chilean standard imposes no restrictions on buildings with structural irregularities. In such cases, these irregularities only impact the seismic analysis methodology.

When a structure is regular in both plan and elevation, all assessed standards permit a seismic analysis using the method of equivalent forces. However, differences arise when the structure is classified as irregular, either in plan, elevation or both, where a modal dynamic analysis is predominantly recommended.

Although not all analysed seismic codes display the same level of development and approach to the subject matter, it is evident that all seismic standards address the issue of structural irregularities. Nevertheless, Chile's standard stands out as the only one lacking well-defined criteria for irregularities. Furthermore, some norms are ambiguous, making it challenging to comprehend the extent of the impact caused by irregularities. Additionally, while certain criteria are repeated across different standards, the allowed limits may vary in accordance with the seismic activity expected in each respective country.

Funding: This research was funded by national funds through the FCT/MCTES (PIDDAC), under the project DRI/India/0645/2020—Evaluation and Retrofitting of Existing Buildings for Safe and Sustainable Built Environment (https://doi.org/10.54499/DRI/India/0645/2020), and by Base Funding—UIDB/04708/2020 and Programmatic Funding—UIDP/04708/2020 of the CONSTRUCT—Instituto de I&D em Estruturas e Construções—funded by national funds through the FCT/MCTES (PID-DAC).

Acknowledgments: The authors would like to express their gratitude to the editors and reviewers for their constructive comments, which greatly improved the quality of this paper.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Braga, F.; Manfredi, V.; Masi, A.; Salvatori, A.; Vona, M. Performance of Non-Structural Elements in RC Buildings during the L'Aquila, 2009 Earthquake. *Bull. Earthq. Eng.* **2011**, *9*, 307–324. [CrossRef]
2. Verderame, G.M.; De Luca, F.; Ricci, P.; Manfredi, G. Preliminary Analysis of a Soft-Storey Mechanism after the 2009 L'Aquila Earthquake. *Earthq. Eng. Struct. Dyn.* **2011**, *40*, 925–944. [CrossRef]
3. Palermo, M.; Hernandez, R.R.; Mazzoni, S.; Trombetti, T. On the Seismic Behavior of a Reinforced Concrete Building with Masonry Infills Collapsed during the 2009 L'aquila Earthquake. *Earthq. Struct.* **2014**, *6*, 45–69. [CrossRef]
4. Vuran, E.; Serhatoğlu, C.; Timurağaoğlu, M.Ö.; Smyrou, E.; Bal, İ.E.; Livaoğlu, R. Damage Observations of RC Buildings from 2023 Kahramanmaraş Earthquake Sequence and Discussion on the Seismic Code Regulations. *Bull. Earthq. Eng.* **2024**, 1–30. [CrossRef]
5. Tena-Colunga, A. Conditions of Structural Irregularity. Relationships with Observed Earthquake Damage in Mexico City in 2017. *Soil Dyn. Earthq. Eng.* **2021**, *143*, 106630. [CrossRef]
6. Varum, H.; Melo, J.; Furtado, A.; Lima, A. Irregularities in RC Buildings: Perspectives in Current Seismic Design Codes, Difficulties in Their Application and Further Research Needs. In *Seismic Behaviour and Design of Irregular and Complex Civil Structures IV*; Geotechnical, Geological and Earthquake Engineering; Bento, R., De Stefano, M., Köber, D., Zembaty, Z., Eds.; Springer International Publishing: Cham, Switzerland, 2022; Volume 50, ISBN 978-3-030-83220-9.
7. Jara, J.M.; Hernández, E.J.; Olmos, B.A.; Martínez, G. Building Damages during the September 19, 2017 Earthquake in Mexico City and Seismic Retrofitting of Existing First Soft-Story Buildings. *Eng. Struct.* **2020**, *209*, 109977. [CrossRef]
8. Ruggieri, S.; Porco, F.; Uva, G. A Practical Approach for Estimating the Floor Deformability in Existing RC Buildings: Evaluation of the Effects in the Structural Response and Seismic Fragility. *Bull. Earthq. Eng.* **2020**, *18*, 2083–2113. [CrossRef]
9. Ruggieri, S.; Vukobratović, V. The Influence of Torsion on Acceleration Demands in Low-Rise RC Buildings. *Bull. Earthq. Eng.* **2024**, 1–36. [CrossRef]
10. Landge, M.V.; Ingle, R.K. Comparative Study of Floor Response Spectra for Regular and Irregular Buildings Subjected to Earthquake. *Asian J. Civ. Eng.* **2021**, *22*, 49–58. [CrossRef]
11. Das, P.K.; Dutta, S.C.; Datta, T.K. Seismic Behavior of Plan and Vertically Irregular Structures: State of Art and Future Challenges. *Nat. Hazards Rev.* **2021**, *22*, 04020062.
12. Ainuddin, S.; Mukhtar, U.; Ainuddin, S. Public Perception about Enforcement of Building Codes as Risk Reduction Strategy for Seismic Safety in Quetta, Baluchistan. *Int. J. Disaster Risk Reduct.* **2014**, *9*, 99–106. [CrossRef]
13. Mouhine, M.; Hilali, E. Seismic Vulnerability Assessment of RC Buildings with Setback Irregularity. *Ain Shams Eng. J.* **2021**, *13*, 101486. [CrossRef]
14. Georgoussis, G.K. Simplified Dynamic Analysis of Eccentric Buildings with a Setback. 1: The Effect of Mass Irregularity. *Struct. Des. Tall Spec. Build.* **2011**, *20*, 911–927. [CrossRef]
15. Ruggieri, S.; Uva, G. Accounting for the Spatial Variability of Seismic Motion in the Pushover Analysis of Regular and Irregular RC Buildings in the New Italian Building Code. *Buildings* **2020**, *10*, 177. [CrossRef]
16. Men, J.J.; Zhou, Q.; Shi, Q.X. Fragility Analysis Method for Vertically Irregular Reinforced Concrete Frame Structures. *Key Eng. Mater.* **2009**, *400*, 587–592. [CrossRef]
17. Bento, R.; Azevedo, J. Behaviour Coefficient Assessment for Soft Storey Structures. In Proceedings of the Twelfth World Conference on Earthquake Engineering, Auckland, New Zealand, 30 January–4 February 2000; pp. 1–8.
18. Kassem, M.M.; Mohamed Nazri, F.; Wei, L.J.; Tan, C.G.; Shahidan, S.; Mohd Zuki, S.S. Seismic Fragility Assessment for Moment-Resisting Concrete Frame with Setback under Repeated Earthquakes. *Asian J. Civ. Eng.* **2019**, *20*, 465–477. [CrossRef]
19. Oggu, P.; Gopikrishna, K. Assessment of Three-Dimensional RC Moment-Resisting Frames under Repeated Earthquakes. *Structures* **2020**, *26*, 6–23. [CrossRef]
20. Kappos, A.J.; Scott, S.G. Seismic Assessment of a R/C Building with Setbacks Using Nonlinear Static and Dynamic Analysis Procedures. In Proceedings of the 6th SECED Conference, Seismic Design Practice into the Next Century, Oxford, UK, 26–27 March 1998; pp. 1–8.
21. Lima, A.G.; Melo, J.; Varum, H. Structural Irregularities in the Seismic Design of Reinforced Concrete Buildings: Discussion of Regulatory Requirements and Case Studies. *Rev. Port. Eng. Estrut.* **2021**, *3*, 75–86.
22. Das, S. *Seismic Design of Vertically Irregular Reinforced Concrete Structures*; North Carolina State University: Raleigh, NC, USA, 2000; ISBN 0493465618.
23. Alecci, V.; De Stefano, M. Building Irregularity Issues and Architectural Design in Seismic Areas. *Frat. Integrita Strutt.* **2019**, *13*, 161–168. [CrossRef]
24. De Stefano, M.; Pintucchi, B. A Review of Research on Seismic Behaviour of Irregular Building Structures since 2002. *Bull. Earthq. Eng.* **2008**, *6*, 285–308. [CrossRef]
25. Bhosale, A.; Davis, R.; Sarkar, P. New Seismic Vulnerability Index for Vertically Irregular Buildings. *ASCE ASME J. Risk Uncertain. Eng. Syst. A Civ. Eng.* **2018**, *4*, 04018022. [CrossRef]
26. Athanatopoulou, A.M.; Manoukas, G.E. Torsional Sensitivity Criteria In Seismic Codes. *Earthq. Struct.* **2021**, *21*, 1–10. [CrossRef]
27. Varum, H.; Furtado, A.; Melo, J. Insights on the Seismic Design of Current RC Buildings: Field Lessons, Codes and Research Needs. In Proceedings of the European Conference on Earthquake Engineering and Seismology, Bucharest, Romania, 4–9 September 2022; pp. 311–322.
28. De S.A. Ferreira, M.M.L. *Risco Sísmico Em Sistemas Urbanos*; Universidade Técnica de Lisboa: Lisboa, Portugal, 2012.

29. Zhao, C.P.; Chen, Z.L.; Zhou, L.Q.; Li, Z.X.; Kang, Y. Rupture Process of the Wenchuan M8.0 Earthquake of Sichuan China: The Segmentation Feature. *Chin. Sci. Bull.* **2010**, *55*, 284–292. [CrossRef]
30. Liu-Zeng, J.; Zhang, Z.; Wen, L.; Tapponnier, P.; Sun, J.; Xing, X.; Hu, G.; Xu, Q.; Zeng, L.; Ding, L.; et al. Co-Seismic Ruptures of the 12 May 2008, Ms 8.0 Wenchuan Earthquake, Sichuan: East-West Crustal Shortening on Oblique, Parallel Thrusts along the Eastern Edge of Tibet. *Earth Planet Sci. Lett.* **2009**, *286*, 355–370. [CrossRef]
31. Costa, A.A.; Ferreira, M.A.; Oliveira, C.S. O Grande Sismo de Sichuan: Impactos e Lições Para o Futuro. In Proceedings of the Sismica 2010—8° Congresso de Sismologia e Engenharia Sísmica, Aveiro, Portugal, 20 October 2010; pp. 1–31.
32. Rodrigues, H.; Romão, X.; Costa, A.G.; Arêde, A.; Varum, H.; Guedes, J.; Vicente, R.; Costa, A.A.; Pauperio, E. Sismo de L'Aquila de 6 de Abril de 2009 Ensinamentos Para Portugal. In Proceedings of the Sismica 2010—8° Congresso de Sismologia e Engenharia Sísmica, Aveiro, Portugal, 20 October 2010; pp. 1–14.
33. Romão, X.; Costa, A.A.; Paupério, E.; Rodrigues, H.; Vicente, R.; Varum, H.; Costa, A. Field Observations and Interpretation of the Structural Performance of Constructions after the 11 May 2011 Lorca Earthquake. *Eng. Fail. Anal.* **2013**, *34*, 670–692. [CrossRef]
34. Magliulo, G.; Ercolino, M.; Petrone, C.; Coppola, O.; Manfredi, G. The Emilia Earthquake: Seismic Performance of Precast Reinforced Concrete Buildings. *Earthq. Spectra* **2014**, *30*, 891–912. [CrossRef]
35. Bournas, D.A.; Negro, P.; Taucer, F.F. Performance of Industrial Buildings during the Emilia Earthquakes in Northern Italy and Recommendations for Their Strengthening. *Bull. Earthq. Eng.* **2014**, *12*, 2383–2404. [CrossRef]
36. Novelli, V.; Alexander, D.; Verrucci, E. *The 29th May 2012 Emilia Romagna Earthquake EPICentre Field Observation Report No. EPI-FO-290512*; UCL EPICentre: London, UK, 2012.
37. Varum, H.; Furtado, A.; Rodrigues, H.; Dias-Oliveira, J.; Vila-Pouca, N.; Arêde, A. Seismic Performance of the Infill Masonry Walls and Ambient Vibration Tests after the Ghorka 2015, Nepal Earthquake. *Bull. Earthq. Eng.* **2017**, *15*, 1185–1212. [CrossRef]
38. Rodrigues, H.; Furtado, A.; Vila-Pouca, N.; Varum, H.; Barbosa, A.R. Seismic Assessment of a School Building in Nepal and Analysis of Retrofitting Solutions. *Int. J. Civ. Eng.* **2018**, *16*, 1573–1589. [CrossRef]
39. Dizhur, D.; Dhakal, R.P.; Bothara, J.; Ingham, J.M. Building Typologies and Failure Modes Observed in the 2015 Gorkha (Nepal) Earthquake. *Bull. N. Z. Soc. Earthq. Eng.* **2016**, *49*, 211–232. [CrossRef]
40. Conde, F.R. *Avaliação Da Capacidade Sismo-Resistente de Edifícios Em Alvenaria Segundo a NTC-2017*; Faculdade de Engenharia da Universidade do Porto: Porto, Portugal, 2018.
41. *EN 1998-1:2005*; Eurocode 8—Design of Structures for Earthquake Resistance—Part 1–1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 2005.
42. *EN 1992-1-1:2004*; Eurocode 2—Design of Concrete Structures—Part 1–1: General Rules and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 2004.
43. *PrEN1998-1-2:2024*; Eurocode 8: Design of Structures for Earthquake Resistance—Part 1-2: Rules for New Buildings, Draft Post-ENQ 48th Meeting CEN/TC250/SC8. European Committee for Standardization: Brussels, Belgium, 2024.
44. *NBR 15421*; Projeto de Estruturas Resistentes a Sismos—Procedimento. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2023.
45. *NBR 6118*; Projeto de Estruturas de Concreto—Procedimento. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2023.
46. *NTC-RSEE*; Administración Pública de la Ciudad de México Norma Técnica Complementaria Para La Revisión de La Seguridad Estructural de Las Edificaciones. Órgano de Difusión del Gobierno de la Ciudad de México: México City, Mexico, 2017.
47. *MOC-2015*; Manual de Diseño de Obras Civiles: Diseño Por Sismo. Comisión Federal de Electricidad: México City, Mexico, 2015.
48. *ASCE/SEI7-22*; Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers: Reston, VA, USA, 2021.
49. *NCH 433-1996 Modificada En 2012*; Diseño Sísmico de Edificios. Instituto Nacional de Normalizacion: Santiago, Chile, 2012.
50. *NCh 2369*; Diseño Sísmico de Struturas e Instalaciones Industriales. Instituto Nacional de Normalizacion: Santiago, Chile, 2003.
51. *NCh 2745*; Análisis y Diseño de Edificios con Aislación Sísmica. Instituto Nacional de Normalizacion: Santiago, Chile, 2013.
52. *NCh 3411*; Diseño Sísmico de Edificios con Sistemas Pasivos de Disipación de Energia. Instituto Nacional de Normalizacion: Santiago, Chile, 2017.
53. *NCh 3357*; Diseño Sísmico de Componentes y Sistemas no Estructurales. Instituto Nacional de Normalizacion: Santiago, Chile, 2015.
54. *NZS 1170-5*; Structural Design Actions—Part 5: Earthquake Actions—New Zealand Commentary. Standards New Zealand: Wellington, New Zealand, 2004.