Summary

The present PhD dissertation aims at exploring possible design enhancements for the robustness of new reinforced concrete (RC) ordinary buildings designed in seismic area, against a supporting column removal scenario. At present, actual code rules lack in providing indications on the safety levels that a RC building should guarantee against a column removal scenario, but mainly prescriptive rules are recommended.

Chapter 1 is about a deep overview of the basic concepts behind structural robustness. At first, an examination is given about the historical context that has driven the development of structural robustness principles, together with fundamental definitions related to progressive and disproportionate collapse found in existing literature. Next, the concept of the risks associated with progressive collapse is defined, emphasizing the ongoing need for research in this field. The chapter also discusses strategies outlined in current guidelines and building codes aimed at mitigating the risks of progressive collapse. An analysis of key indicators used to quantify and measure structural robustness is presented. Finally, the chapter focuses on the structural response of cast-in-situ reinforced concrete (RC) structures when subjected to abnormal scenarios such as column removal.

Chapter 2 discusses the fundamental concepts for the formulation of structural reliability analysis. It starts with an introduction to probabilistic analysis, outlining the basics of this analytical approach. Then, an overview of the primary uncertainties that impact structural engineering problems is provided, distinguishing between aleatory and epistemic ones. Furthermore, the chapter delves into the definition of the Limit State Function and assesses the performance requirements that must be ensured for new structures. Lastly, it explores various reliability methods, including level III, level II, level I, and level 0 methods, discussing their characteristics and applications.

Chapter 3 describes the case study involving the application and discussion of robustness design improvements. It begins with an overview of the seismic design procedure for two multistorey reinforced concrete buildings, one composed by only seismic resistant frames as much regular as possible and the second one constituted

by both seismic resistant and secondary frames with different dimensions of beams and columns. Following that, it explains the finite element modelling assumptions used to conduct all the non-linear analyses performed within this dissertation. The modelling assumptions are based on the validation against an experimental test of a beam-column subassembly extracted from a building designed in seismic area. In addition, the method adopted to model the contribution of the orthogonal two-dimensional framed system, by means of equivalent springs, is explained. These equivalent springs are placed in the beam-column nodes of each frame under study and are calibrated both with a linear and non-linear approach.

Chapter 4 illustrates and justifies many design modifications on the longitudinal reinforcement arrangement, implemented to enhance the structural robustness of the RC buildings. Then, a detailed deterministic parametric analysis is carried out to evaluate the effectiveness of various design suggestions in enhancing structural robustness. These modifications are applied to the longitudinal reinforcement of the beams and are: *support continuity*, *continuity*, *symmetry in cross-section* of longitudinal reinforcement, enhancement of Vierendeel behavior by placing both *global* and *partial equal* reinforcement among the floors and the influence of *side face reinforcement bars*. In addition, the 3D effects exerted by the orthogonal (out-of-plane) framed system on the two-dimensional frames is studied by considering the influence of equivalent translational elastic springs placed in each beam-column node. To compare these enhancements, non-linear finite element (NLFE) pushdown analyses are developed, applying a monotonically increasing vertical displacement at the point of column removal and registering the corresponding reaction. Two distinct failure scenarios are considered during the analyses. The findings indicate significant improvements in structural robustness for the proposed solutions, particularly concerning the efficacy of *side face reinforcement bars* in enhancing both flexural and catenary behavior.

Chapter 5 is about the probabilistic assessment of the robustness of three different configurations selected as the most relevant frames according to the results of the deterministic analyses given in the previous chapter. One frame is designed according to actual code rules and other two are obtained by applying the robustness improvements proposed in the previous chapter. In all the three frames the contribution of the orthogonal framed system is accounted for by means of equivalent elastic springs placed on beam-column nodes. The reliability assessment is conducted using a strain-based 5-step procedure employing a full probabilistic approach (i.e., considering aleatory properties of both materials and loads), generating for each of the basic variables 100 realizations. Subsequently, displacement-controlled pushdown NLFE analyses are performed on the 300 sampled models to determine energy-based dynamic amplification factors. Then, probabilistic static-equivalent NLFE analyses are executed for the 300 realizations, simulating a central supporting column removal and appropriately amplifying the gravity loads on the central spans. The strains of both confined concrete and reinforcement at various points are monitored and probabilistically modelled. Ultimately, convolution integrals between aleatory strains and corresponding aleatory ultimate thresholds are computed to derive failure probabilities concerning the ultimate limit state. The results provide insights into the reliability levels of structural elements within the three configurations, highlighting important safety advantages when adopting robustness improvements. In this way, the proposed solutions, demonstrated effective, sustainable and safe, are studied in the next chapter in order to deterministically evaluate the 3D global response.

Chapter 6 aims at assessing the robustness of the 3D structure analyzing the deterministic response of the two frames directly involved in the failure scenario in the orthogonal directions. In detail, the building is composed by both seismic resistant frames and secondary frames and the three structural configurations already analyzed from a reliability point of view are investigated. For each of the three design configurations, four different failure scenarios are considered, involving the removal of specific supporting columns. In addition, the contribution of the frame, located along the orthogonal (out-of-plane) direction, is considered by means of non-linear translation springs. The results demonstrate the importance of calibrating the non-linear constitutive laws of the springs, especially, for large vertical displacements and for frames having wide beams due to their large contribution in terms of ductility. By comparing the results of the superimposed capacity curve of the frames in the two orthogonal directions and the one obtained from a 3D analysis, the validation of the superposition principle is obtained. This confirms the possibility of designing a 3D structure in terms of robustness without the need of developing a full 3D analysis but focusing on the design of planar frames. Finally, the energetic equivalence approach is applied on the achieved global capacity curves to highlight the benefits of the robustness design improvements.