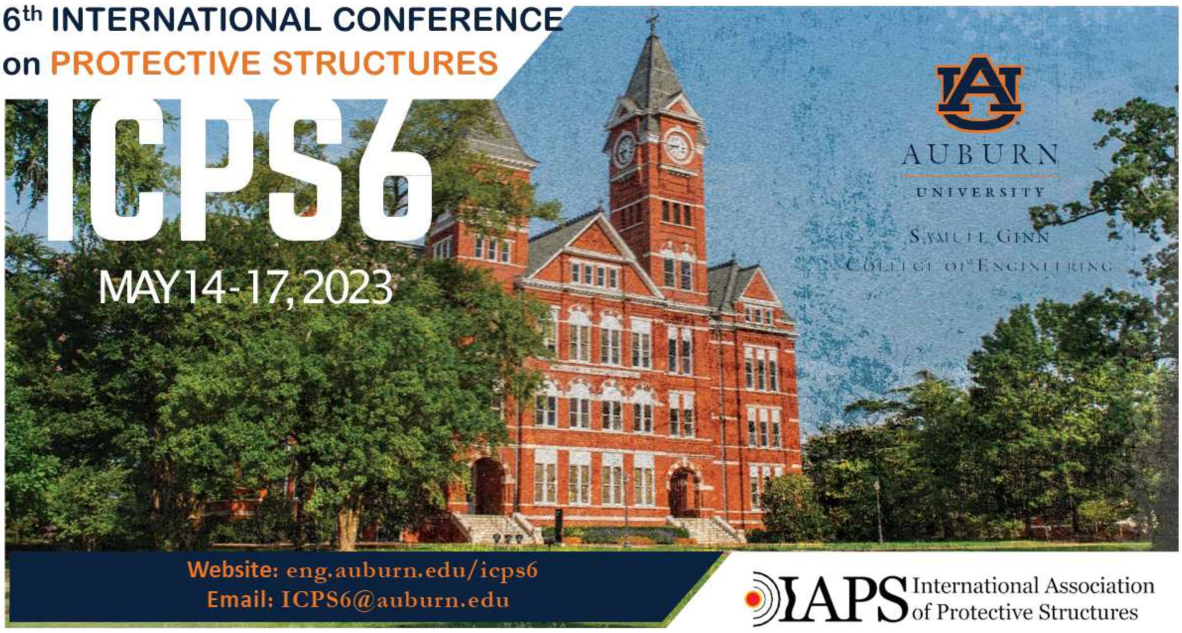

Proceedings of the
6th International Conference on
Protective Structures

CONFERENCE CHAIRPERSONS AND EDITORS:

James S. Davidson
Gottlieb Professor of Structural Engineering, Auburn University

Catherine S. Stephens
Director, International Research Office
U.S. Army Engineer Research and Development Center

THANK-YOU TO OUR PARTNERS AND SPONSORS:

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

ERDC WERX

Viper Applied Science

STONE Security Engineering

ISBN: 979-8-218-31237-4
V28OCT2023

6th International Conference on Protective Structures (ICPS6)
14 – 17 May 2023, Auburn University USA

PAPER 154
IMPROVING BUILDING ROBUSTNESS THROUGH FUSE-SEGMENTATION

Nirvan Makoond[1], Manuel Buitrago[2], Jose M. Adam[3]
ICITECH, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain.

[1] Postdoctoral researcher, ncmakoon@upv.es (corresponding author)
[2] Postdoctoral researcher, mabuimo1@upv.es
[3] Professor, joadmar@upv.es

ABSTRACT
As the impacts of climate change and emerging conflicts become more and more apparent, it is undeniable that more robust building structures are required for resilient societies to be able to thrive. In fact, there has been a growing research effort over the past few decades on structural robustness and progressive collapse. As a result, several building codes now include specific provisions for improving the progressive collapse resistance of building structures. At present, almost all methods for improving structural robustness included in relevant codes rely on providing extensive continuity within a structural system to ensure that alternative load paths are available to redistribute loads supported by a structural component after its failure. Although this approach has proven to be effective in many cases, certain situations do exist for which it may increase the risk of disproportionate collapse. These include, for example, cases of large initial failure or of buildings with wide spans between columns. In such situations, the remaining parts of a structural system may not be able to find a stable state of equilibrium after initial failure. Having extensive continuity can contribute to the collapsing part pulling down the rest of the structure. A possible approach for arresting failure propagation in these situations involves segmenting building structures. In fact, there exist several examples of real occurrences when the extent of a collapse was limited thanks to a building being segmented into different parts. This includes the partial collapse of the Pentagon (Washington, 2001) and of the terminal 2E building at Charles de Gaulle airport (Paris, 2004). Although segmentation was not necessarily introduced in building design for improving robustness in these cases, they do demonstrate its effectiveness in limiting the extent of progressive collapse. However, segmentation with weak borders does interrupt continuity, which has already proven its efficiency for redistributing loads in the case of small initial failures. To overcome this limitation, there exists the possibility of using structural fuses to connect different segments of a structure. Such fuses should be able to provide continuity for normal and accidental design situations considered by current building codes but would separate building segments when failure propagation is inevitable. In fact, a novel fuse-based segmentation design approach to limit the propagation of failures in building structures is currently being developed by the Endure project thanks to a grant of €2.5 million awarded by the European Research Council. This paper presents the framework being used within this project to i) develop a performance-based approach for the design of fuse-segmented buildings, ii) design and test structural fuses for selected building types, and iii) implement and validate the performance of structural fuses in full-scale buildings.

Keywords: Robustness, Extreme events, Progressive collapse, Segmentation, Structural fuses

INTRODUCTION

Both natural and man-made disasters often cause local-initial damage to critical elements of buildings. Such initial local failures can in turn propagate within the structure, through a phenomenon known as progressive collapse, resulting in a disproportionate final damaged state. There exist several known cases whereby such failures have led to grave negative consequences that have come at a great cost to the affected societies (e.g. Ronan Point Tower in London in 1968; Capitán Arenas Apartment Block in Barcelona in 1972; the A.P. Murrah Federal Building in Oklahoma in 1995; the Sampoong Department Store in Seoul in 1995; the Hard Rock Hotel in New Orleans in 2019; the Champlain Towers South in Miami in 2021). Some of the aforementioned events have motivated the adoption of new provisions in building codes and have acted as catalysts for investment in research on the topic. As a result, the concept of structural robustness has emerged as being of particular interest for the reduction of risks related to progressive collapse since it can be defined as a structure's insensitivity to local damage [1].

Most current design philosophies targeting progressive collapse, including those specified in building codes, aim to improve structural robustness by providing extensive continuity. Typically, this is achieved by complying with prescriptive tying force requirements or by ensuring that Alternative Load Paths (ALPs) are available after the loss of specific structural components. Such methods are included in several international codes, including European standards such as EN 1991-1-7 [2] and North American ones such as UFC-4-023-03 [3]. Although this strategy focusing on continuity has been shown to be valid for certain situations, notably when the initial failure is small, it can be harmful in certain scenarios by helping the propagation of failure and resulting in disastrous consequences [4]. In fact, there exists several examples that clearly demonstrate how continuity can actually increase the risk of progressive collapse, notably the failure of the Haeng-Ju Grand Bridge in 1992 [5]. In this case, continuous post-tensioning over 11 spans caused complete collapse as 10 spans were pulled down following the failure of a single span during construction. The common occurrence of rack failures in warehouses also make it evident that continuity is not always a good choice for structural robustness. This situation, whereby continuity contributes to the onset of progressive collapse, also occurs in buildings, as has been found by firefighters [6] and demolition experts [7].

Several authors have highlighted the urgent need to define new design approaches to address these clear shortcomings of building codes with respect to progressive collapse, particularly due to the unpredictable nature of extreme abnormal events, which means that potential harmful impacts of the limitations cannot be properly evaluated. One of the most promising possible approaches that have been mentioned [1,8,9] involves segmenting buildings into different parts to prevent failures from one zone propagating to others. While it is important to highlight that segmentation can be achieved through strong or weak borders [4], the scope of the work presented in this article is limited to segmentation achieved through structural discontinuity (i.e. weak borders). In fact, although this form of segmentation is commonly used as a control measure against thermal expansion and seismic movements, it has not yet been used to design robust buildings resistant to progressive collapse.

Nevertheless, while segmentation through structural discontinuity could prove to be effective for improving robustness in certain situations, the lack of continuity it entails certainly appears to contravene most current design philosophies. This has led some authors [1,8,10] to mention the possibility of using fuses to join the different building segments. Such fuses should be able to transfer ordinary design loads as well as accidental design situations considered in current building codes. However, should a situation arise whereby the forces generated by a local failure could pull down the rest of the structure or a disproportionately large part of it, fuses should fail to provide load transfer, thus segmenting the structure and preventing damage propagation.

They can therefore be seen as smart switch devices able to provide either continuity or segmentation only when required. Another advantage of such a design approach to structural robustness is that it can allow other aspects of resilience such as the recovery of essential functions to be explicitly included more easily at the design stage. This can be achieved by including relevant criteria related to the functionality of the building when making design decisions on segmentation.

Despite its potential, this design approach has not yet been backed up by any research and there are not yet any design recommendations to put it into practice. Moreover, before actual fuses can be designed, manufactured, and tested, the situations for which they could be beneficial need to be systematically identified and the criteria that need to be considered when implementing them need to be defined. As such, a framework has been defined as part of the Endure project for the holistic development of structural fuses for enhancing robustness. This does not only include the elaboration of a performance-based approach after gaining an improved understanding of relevant situations and criteria but extends to designing structural fuses for selected building types and testing their effectiveness in full-scale structures.

This article first presents the analysis of past collapses, computational simulations of generic cases, and consequence modelling being performed in order to develop a performance-based approach for the fuse-segmentation design of buildings. Key aspects of the design, testing, and implementation of structural fuses are then described in subsequent sections.

DEVELOPMENT OF A PERFORMANCE-BASED APPROACH

Before being able to develop a performance-based approach for the design of fuse-segmented buildings, it was deemed necessary to systematically identify situations for which segmentation through structural discontinuity can be beneficial. To achieve this, a number of generic building designs were defined based on different combinations of the following key parameters: structural typology, floor area, number of bays, span between columns, number of storeys, floor-to-ceiling height and regularity in plan. Since structural discontinuity is clearly most effective for stopping horizontal failure propagation, the initial set of generic designs defined were limited to buildings covering large areas and with the number of floors limited to 3 storeys. At the same time, a number of threat-independent scenarios not currently considered by the alternate path method specified in UFC-4-023-03 [3] were defined. Specifically, two types of scenarios were defined: i) failure of a single column and the beam-column connection above it (as opposed to assuming that the connection remains intact) and ii) failure of two columns.

To support the definition of the generic designs and threat-independent scenarios, more than 30 real cases of partial or complete building collapse were studied in great detail. Key information was systematically recorded relating to: i) the context of the failure event, ii) the structural typology, iii) the geometry, iv) the extent of initial failure as well as its propagation, and v) the consequences of the collapse. Detailed outcomes from this analysis are presented in [11], but it is worth noting that many cases were characterised by the initial failure of more than one structural component. Specifically, initial failure of 2 or more columns occurred in 8 cases and initial failure of 2 or more beams occurred in 3 cases. In addition, 4 cases were characterised by the initial failure of joints. This demonstrates the relevance of the chosen threat-independent scenarios and underlines the limitations of the most widely used methods included in building codes for improving robustness.

To systematically compare the performance of unsegmented and segmented configurations of the generic designs, three key performance indicators (KPIs) were selected and a methodology for estimating their expected value based on total collapse area and collapsed elements was developed. The three KPIs employed are: loss of life, reconstruction and landfill costs, and CO_2 emitted during clean-up and reconstruction. Since data on the number of casualties was collected as part of the previously described analysis of case studies, two existing empirical models [12,13] for estimating casualties in a building collapse could be evaluated. The results of this comparison are also presented in [11] and revealed that the model proposed by Hingorani et al. [13] is more suitable to be used for the consequence modelling to be performed during the development of this performance-based approach. Reconstruction costs and CO_2 emissions are being computed using a similar approach as that presented in [14].

In a first instance, the scope of the performance-based approach to be developed is to be limited to two of the most widely used building types, namely multi-storey frame structures made of i) reinforced concrete (RC) or ii) steel with composite slabs. As such, typical designs of these types were defined and studied first. To allow for a greater number of cases to be studied, a methodology for estimating progressive collapse potential with sufficient accuracy using simplified models is currently being developed. Nevertheless, nonlinear dynamic simulations of different generic cases have already been performed using the applied element method (AEM) [15].

Figure 1 shows the predicted evolution of damage after removal of a penultimate interior column from one of the generic RC designs, while Figure 2 shows the predicted evolution of damage after the removal of the two columns indicated in the figure. This particular generic case is characterised by a span between column of 10 m, a floor area of 900 m^2 and 3 floors. It is important to point out that the building complies with all design requirements stipulated in Eurocode 2 [16] for a building in Valencia, Spain. In addition, continuous tying reinforcement was included in the design. The dimensions of these elements complied with the prescriptive rules outlined in EN 1991-1-7 [2] and also those outlined in UFC-4-023-03 [3]. This means that the building complies with all robustness design requirements of a building of consequence class 2B (according to EN 1991-1-7) and of risk category II (according to UFC-4-023-03).

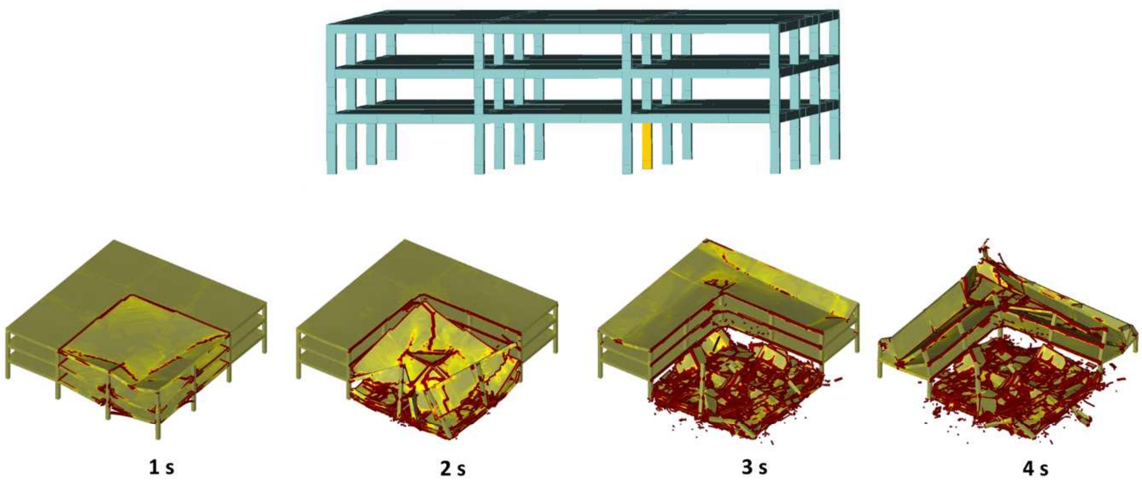

Figure 1. Simulation of typical multi-storey RC frame structure after sudden removal of penultimate interior column. Damage is shown at different times (in seconds) after column removal.

As can be observed in Figure 1, despite complying with robustness design requirements stipulated in current building codes, total collapse of this typical multi-storey RC frame structure could occur if a single penultimate interior column were to be removed. Naturally, total collapse could also be expected to occur after the loss of two columns (Figure 2). As shown, the collapse in this case would propagate more rapidly.

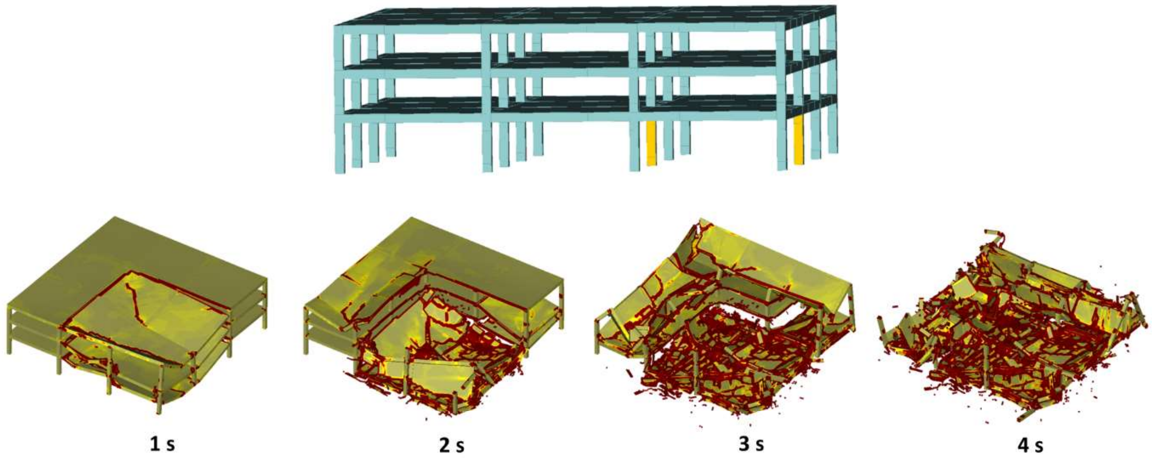

Figure 2. Simulation of typical multi-storey RC frame structure after sudden removal of two columns. Damage is shown at different times (in seconds) after removal of both columns.

In both aforementioned scenarios, the extent of collapse would clearly not have extended to the entire structure had it been separated into different segments by structural discontinuities. Different possible segmentation configurations are currently being evaluated for all generic cases in scenarios for which significant failure propagation is observed based on simulation results. Their benefits in terms of consequences considering these scenarios are being used to select some of the most suitable segmentation configurations for the defined cases.

Next, scenarios for which the previously identified suitable segmentation configurations are most disadvantageous will be listed and systematically studied for each generic case. It is important to note that the structural fuse itself is still not considered at this stage. Scenarios involving horizontal loading (such as those caused by strong winds or earthquakes) are likely candidates to be considered at this point since the loss of continuity that comes with segmentation is likely to result in a loss of capacity to resist lateral loads. The results of this analysis should allow to define a prioritised list of most unfavourable scenarios for segmented configurations of each typology.

Finally, results from the analyses of favourable and unfavourable scenarios for segmentation will be directly employed to propose a Multi-Criteria Decision Analysis (MCDA) framework to enable preliminary decisions on the positioning and design requirements of structural fuses. The previously performed consequence analyses will then be updated by now considering the structural fuses. The probability of the different system failure events studied will also be estimated to allow for quantitative risk analyses of unsegmented and fuse-segmented building structures for all the scenarios studied. This more detailed assessment should facilitate effective communication of the risks associated to fuse-segmentation. Finally, models for converting the different KPIs used to monetary terms will be employed or developed with the aim of estimating the maximum amount that fuse-segmentation should cost to maintain a positive expected societal net benefit over the lifetime of a structure.

STRUCTURAL FUSE DESIGN & TESTING

In subsequent phases of the Endure project, simulation results used for the development of the performance-based approach will be used to establish an initial set of loading configurations for which a fuse should ensure load transfer or separate. This will then be used to elaborate and optimise different design options for structural fuses to be used in RC and steel/composite multi-storey frame structures. Ideally, the design should be as simple as possible but still ensuring separation when failure propagation is inevitable. High-fidelity finite element (FE) simulations will be performed in this phase of the project to study the detailed behaviour of structural fuses.

Once a sufficiently optimised design is obtained, pseudo-static laboratory tests on scaled-down subassemblies such as the ones shown in Figure 3 will be performed to ensure that the structural fuses work as expected. These tests will be invaluable for calibrating numerical models and fine-tuning the structural fuse designs.

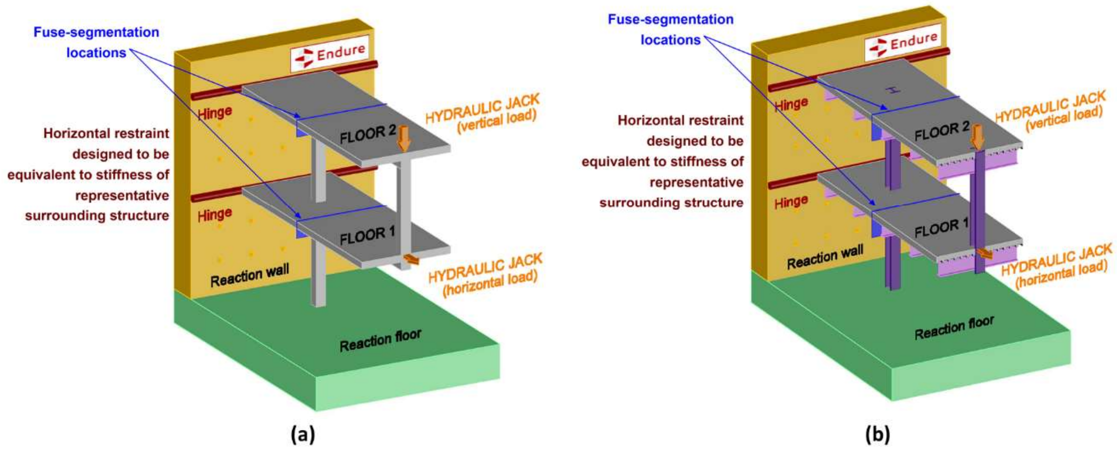

Figure 3. Schematic diagram of possible tests on: (a) RC subassemblies (b) Steel/composite subassemblies

IMPLEMENTATION IN FULL-SCALE STRUCTURES

Once the fuses have been designed and tested in subassemblies, the next phase of the project will involve implementing them in full-scale structures. This phase is considered crucial in order to validate the performance of structural fuses considering dynamic effects and possible debris impact in the absence of possible scale effects. Full-scale specimens of RC and steel/composite multi-storey frame buildings will be built and fitted with structural fuses. At least 3 scenarios will be tested, including i) the undamaged structure with gravity loads that are greater than the load combination specified in codes for accidental design situations, ii) the structure with small initial damage, and iii) the structure with large initial damage (Figure 4(b)).

The structural fuses should be able to ensure load redistribution in the case of the small initial damage (Figure 4(a)), while they should break and prevent further failure propagation in the case of the large initial damage (Figure 4(b)). This validation exercise is considered an important step to demonstrate the effectiveness of this design solution and convince practitioners to use it in industry.

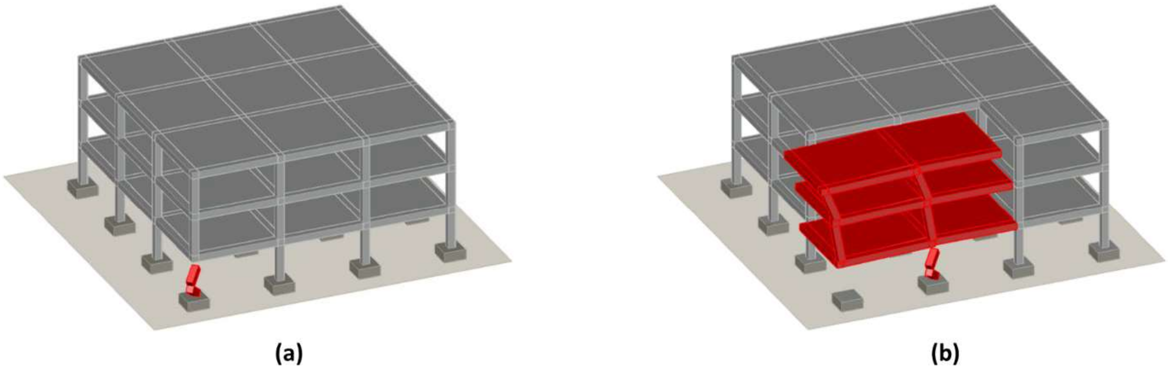

Figure 4. Schematic diagram of tests on full-scale structures: (a) small local-initial failure scenario and (b) large local-initial failure scenario.

CONCLUSIONS

The general framework being employed to develop structural fuses for enhancing robustness has been presented in this article. This work is being performed as part of the Endure project, which has been funded for €2.5 million by the European Research Council.

The development of a performance-based approach for robustness design using this novel approach is described. This includes carrying out a systematic analysis of many past cases of collapse and executing computational simulations of carefully defined generic cases before performing consequence modelling. Some of the most important outcomes from the analysis of past failures have been highlighted and useful insights from results of simulations are also presented. This includes results which show that buildings designed to comply with prescriptive tying force requirements can experience progressive collapse even after the failure of a single component. Some situations for which fuse-segmentation would be beneficial are also briefly presented.

Finally, some of the key aspects of designing and testing structural fuses have also been outlined.

ACKNOWLEDGMENTS

This article is part of a project (Endure) that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 101000396). The authors would also like to express their gratitude for the postdoctoral Grant IJC2020-042642-I funded by MCIN/AEI/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR".

REFERENCES

1. Adam, J. M., Parisi, F., Sagaseta, J. & Lu, X. Research and practice on progressive collapse and robustness of building structures in the 21st century. *Engineering Structures* **173**, 122–149 (2018).
2. European Committee for Standardization (CEN). EN 1991-1-7:2006: Eurocode 1 - Actions on structures - Part 1-7: General actions - accidental actions. at (2006).
3. Department of Defense (DoD). UFC 4-023-03: Unified Facilities Criteria - Design of buildings to resist progressive collapse. at (2016).

4. Starossek, U. *Progressive Collapse of Structures*. *Progressive Collapse of Structures* (ICE Publishing, 2017). doi:10.1680/pcos.61682.

5. The Institution of Structural Engineers (IStructE). Manual for the systematic risk assessment of high-risk structures against disproportionate collapse. at (2013).

6. MMC-NIBS. *Prevention of progressive collapse: Report on the July 2002 National Workshop and recommendations for future efforts*. (2003).

7. Loizeaux, M. & Osborn, A. E. Progressive Collapse—An Implosion Contractor's Stock in Trade. *Journal of Performance of Constructed Facilities* **20**, 391–402 (2006).

8. Starossek, U. & Wolff, M. Design of collapse-resistant structures. in *JCSS and IABSE Workshop on Robustness of Structures* (2005).

9. National Institute of Standards and Technology (NIST). NISTIR 7396: Best practices for reducing the potential for progressive collapse in buildings. 216 at (2007).

10. Osteraas, J. D. Murrah Building Bombing Revisited: A Qualitative Assessment of Blast Damage and Collapse Patterns. *Journal of Performance of Constructed Facilities* **20**, 330–335 (2006).

11. Caredda, G. *et al.* Learning from the progressive collapse of buildings. *Manuscript under review* (2023).

12. Coburn, A. W., Spence, R. J. S. & Pomonis, A. Factors determining human casualty levels in earthquakes: Mortality prediction in building collapse. in *Proceedings of the 10th World Conference on Earthquake Engineering* 5989–5994 (Balkema, 1992).

13. Hingorani, R., Tanner, P., Prieto, M. & Lara, C. Consequence classes and associated models for predicting loss of life in collapse of building structures. *Structural Safety* **85**, 101910 (2020).

14. Janssens, V., O'Dwyer, D. W. & Chryssanthopoulos, M. K. Assessing the Consequences of Building Failures. *Structural Engineering International* **22**, 99–104 (2012).

15. Tagel-Din, H. & Meguro, K. Nonlinear simulation of RC structures using applied element method. *Doboku Gakkai Ronbunshu* **2000**, 13–24 (2000).

16. European Committee for Standardization (CEN). EN 1992: Eurocode 2 - Design of concrete structures. at (2004).