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Enhancing Building Robustness Through a Novel Risk-Based Segmentation Strategy: A Case Study

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Abstract

The disproportionate collapse of building structures is a matter of growing concern. Current design strategies have been shown to have limitations in ensuring adequate robustness when dealing with large initial failures, which can impact the structural safety. This research has developed a novel risk-based strategy to enhance building robustness through segmentation. The proposed methodology involves the identification of an optimal segmentation configuration, with this being based on structural and geometric criteria. Following this, a cost-benefit analysis is developed to evaluate the efficiency of the proposed solution. To illustrate the application of the proposed strategy, a case study has been identified in which the segmentation strategy is applied, and the cost-effectiveness of the identified solution is evaluated.

Keywords: progressive collapse, robustness, segmentation, risk analysis, consequence analysis, break-even approach.

1 Introduction

Extreme events of both natural and man-made origin are increasing in their frequency and intensity. This highlights the need for safe and resilient structures.

Recent cases from the past have shown that unpredictable events are capable of causing local failures within a structural system, which in turn can propagate to other initially unaffected members of the structure. This phenomenon, known as ‘progressive collapse’, can be disproportionate in its ultimate magnitude and catastrophic in its consequences.

Current design codes [1–3] tent to focus on ensuring structural robustness by providing extensive continuity in buildings through design techniques that can be both prescriptive (e.g., the so-called ‘tie force rules’) and performance-based (e.g., the alternative load path method) [4]. The effectiveness of these strategies is well known when dealing with hazards that cause small initial failures in structures. However, as recognized by firefighters and demolition experts, for larger initial damage, an extensive continuity can actually promote failure propagation rather than limiting it [5].

An alternative strategy, called ‘segmentation’, focuses on isolating the collapse, when its initiation is unavoidable, by dividing the structure into units referred to as segments. It has been shown empirically that segmentation can be effective in arresting the spread of collapse. In fact, previous cases such as the partial collapses of the Pentagon in Washington DC (USA, 2001) and Charles de Gaulle Airport in Paris (France, 2004) demonstrate that, particularly in structures mainly oriented along horizontal axes (such as low-rise buildings), segmentation can be a valid solution to limit the consequences of horizontal failure propagation (e.g., zipper- and domino-type propagation phenomena [6]). However, there is a lack of clarity in the definition and in the scope of application of segmentation, as well as the absence of explicit guidelines to assist designers in segmenting buildings [7].

The *Endure* project [8] aims to address this lack of knowledge by developing a novel design approach called fuse-based segmentation. The objective is to combine the benefits of both continuity and segmentation to provide a new line of defence for buildings where continuity cannot ensure the required level of safety. This can be done by (i) developing a performance-based approach to the design of segmented low-rise buildings, (ii) designing the detailing of the segment borders, and (iii) testing the approach on real scale buildings. The focus of this manuscript is on the development of the performance-based approach for fuse-based segmentation design, which is outlined in Section 2. The structural design of a case study, which was identified to illustrate the application of the proposed methodology, is illustrated in Section 3. The application of the segmentation strategy is given in Section 4. The analysis of the cost-effectiveness of segmenting the case study is performed in Section 5. Finally, concluding remarks are given in Section 6.

2 Framework description

The performance-based methodology described here consists of two main phases. The first consists of a framework to identify suitable segmentation configurations based on geometric and structural criteria. The second consists of analysing the cost-effectiveness of the identified configuration(s) in order to identify the optimal one for the case under study.

The first step of the proposed methodology is the initial failure hierarchy verification. It consists of a simplified and conservative verification, at both component- and system-level, of the expected hierarchy of failure between structural members during a collapse. As mentioned in the introduction, segmentation has proven to be effective in limiting the horizontal propagation of collapse. Therefore, the objective of this step is to verify whether the maximum load that can be transferred through the floor system is sufficient to trigger horizontal collapse propagation and failure of vertical load-bearing elements.

If the failure hierarchy verification is fulfilled, i.e., if the maximum load that can be transferred by the horizontal system is not capable of causing an additional structural failure, the further application of segmentation would not be considered necessary. In fact, in this case, the building would be considered to be capable of 'natural' segmentation [9]. Conversely, if this verification is not fulfilled, the second step of the methodology is to determine the reference extension for the segments. To do this, it is proposed to identify the Critical Initial Damage Scenario (CIDS), which is defined as the least extended of all the initial damage scenarios capable of causing disproportionate collapse. An appropriate strategy is to use highly reliable numerical simulations capable of representing all relevant phases of a structural collapse. The numerical simulations should cover different single and multiple column loss scenarios and should be repeated iteratively until the CIDS is identified.

Once the CIDS has been identified, the segmentation pattern must be defined. The configuration must follow the three axioms of: (i) optimal size, (ii) optimal location, and (iii) symmetry. According to the first axiom, the size of each segment should be as close as possible to the extent of the CIDS. In fact, a smaller segment would not be sufficient to isolate the smallest initial damage causing disproportionate collapse, while a larger segment would allow excessive failure propagation. According to the second axiom, if the building cannot be divided exactly into equal segments, the largest segment should be placed in central zones. Indeed, it has been observed that large initial failures in the interior of a building are more likely to result in disproportionate collapse. Finally, according to the third axiom (and due to the threat-independent nature of the proposed approach), segmentation configurations should always be symmetrical about all axes of symmetry in the building plan.

In order to evaluate the cost-effectiveness of the identified configuration, a cost-benefit analysis should be performed, which consists of the final step of the proposed methodology. To do this, the expected benefit, estimated in terms of the expected risk reduction due to the implementation of segmentation, should be compared with the cost of implementing the solution itself. In this sense, the solution can be defined as cost-effective if the benefit exceeds the cost of implementation, i.e.:

$$Risk_{NS} - Risk_S \geq Cost \tag{1}$$

where the subscripts $(\cdot)_{NS}$ and $(\cdot)_S$ represent non-segmented and segmented building configurations, respectively. Risk is defined as the product of the likelihood and the consequences of an event [10]. Therefore, the total risk of a structural collapse can be expressed as shown in the following equation:

$$Risk = P_C \times Loss = \Sigma_H \Sigma_D \, P[H] \times P[D|H] \times P[C|D] \times Loss \tag{2}$$

where P_C is the probability of occurrence of a structural collapse, $P[H]$ is the probability of occurrence of a specific hazard, $P[D|H]$ is the conditional probability of occurrence of a specific initial failure scenario given the occurrence of a hazard,

$P[C|D]$ is the conditional probability of occurrence of partial or total building collapse given the occurrence of an initial failure scenario, and $Loss$ is a suitable function to estimate the consequences of the final collapse state. In order to make the proposed approach threat-independent, it is possible to consider the probability of occurrence of a hazard and the conditional probability of a specific initial failure as a unique independent parameter [11], namely $P_D = P[D] = \Sigma_H \Sigma_D P[H] \times P[D|H]$. Furthermore, in order to rationally study how much segmentation should cost for different design contexts, it is useful to examine the break-even point at which the implementation cost is equal to the expected benefits. Therefore, under the additional hypothesis of having the same $P[D|H]$ for both the unsegmented and the segmented configuration (that is, $P_{D,NS} = P_{D,S}$, a reasonable assumption if employing force-limiting elements along the segment borders [12]), the following equation can be derived by integrating Equation 1 and Equation 2:

$$P_{D,BE} \times (P[C|D]_{NS} \times Loss_{NS} - P[C|D]_S \times Loss_S) = Cost \tag{3}$$

where the subscript $(\cdot)_{BE}$ stands for break-even. From this equation, it is indeed possible to determine the break-even value of the probability of occurrence of structural damage of a given magnitude as a function of the established implementation cost. This means that, given an implementation cost, the proposed solution would be considered cost-effective with respect to any event capable of causing structural damage with a probability of occurrence $P_D \geq P_{D,BE}$.

If the proposed configuration is considered to be cost-effective, the framework described here would be complete. Otherwise, the cost-effectiveness of an alternative segmentation configuration, identified in accordance with the criteria described above, would need to be assessed.

The strategy just described is summarised in Figure 1. Furthermore, its application on a practical case is illustrated in Sections 4 and 5. More details on the framework for identifying suitable segmentation configurations can be found in [12], while the methodology for evaluating the cost-effectiveness of the identified solution is described in [13].

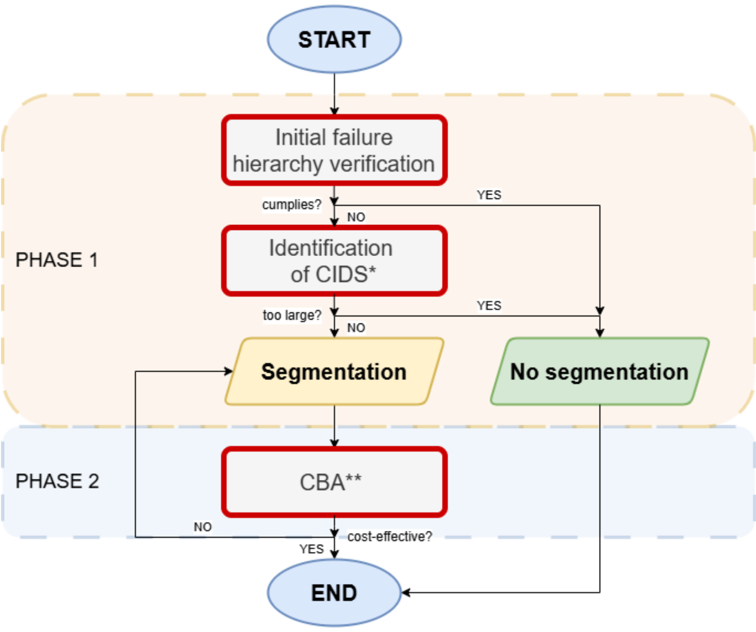

Figure 1. Summary of the proposed methodology for building segmentation. Note that CIDS (*) stands for Critical Initial Damage Scenario, while CBA (**) stands for Cost-Benefit Analysis.

3 Case study

To illustrate the application of the framework described in Section 2, a case study was identified, consisting of a reinforced concrete frame building, characterised by six stories of 4 metres each, and 7 × 3 bays with a span between columns of 10 metres in both directions. The structural design was conducted in accordance with EN 1991 [14], with superimposed dead loads of 2 kN/m^2 and live loads of 3 kN/m^2. The design was carried out using a low ductility class.

With regard to the robustness design, the tie force method of UFC 4-023-03 [1] was adopted to pre-dimension the continuity reinforcement. Furthermore, it was explicitly verified that the building was capable of withstanding the removal of a column as required by the alternative load path method. Further information regarding the design strategy employed to ensure robustness can be found in [12].

The building was provided with two-way slabs of 250 mm thickness and an upper and lower reinforcement mesh consisting of Ø16 mm bars spaced 100 mm apart. The final design of the beams is summarised in Table 1, while that of the columns is summarised in Table 2.

Table 1. Summary of the structural design of the beams.

Beam type (600 mm × 800 mm)	*Long. RFT (Ø20)*				*Trans. RFT (Ø8)*	
	End zones		*Middle zones*		*End zones*	*Middle zones*
	Top	*Bottom*	*Top*	*Bottom*	-	-
All perimeter beams	7	6	3	5	3-legged @100 mm	3-legged @170 mm
Interior beams in outer bays (Floors 1 to 5)	10	7	3	8	3-legged @70 mm	3-legged @150 mm
Interior beams in inner bays (Floors 1 to 5)	9	3	3	6	3-legged @90 mm	3-legged @170 mm
Interior beams in outer bays (Floor 6)	9	9	3	9	3-legged @80 mm	3-legged @150 mm
Interior beams in inner bays (Floors 6)	9	3	3	6	3-legged @80 mm	3-legged @150 mm

Table 2. Summary of the structural design of the columns.

Column type	*Floor*	*Cross-section*	*Long. RFT*		*Trans. RFT (Ø8)*
		Width×Depth [mm×mm]	*Corner bars*	*Additional bars*	-
Corner	Floor 1 to 2	600 × 600	4Ø16	8Ø16	4-legged @240 mm
	Floors 3 to 4	500 × 500	4Ø16	8Ø16	2-legged @120 mm
	Floors 5 to Roof	500 × 500	4Ø16	16Ø16	2-legged @120 mm
Perimeter	Floor 1	600 × 600	4Ø20	20Ø16	3-legged @200 mm
	Floor 2	600 × 600	4Ø20	20Ø16	4-legged @100 mm
	Floors 3 to 4	500 × 500	4Ø20	20Ø16	3-legged @80 mm
	Floors 5 to Roof	500 × 500	4Ø16	20Ø16	3-legged @80 mm
Inner	Floor 1 to 2	600 × 600	4Ø25	24Ø25	2-legged @300 mm
	Floors 3 to 4	500 × 500	4Ø25	24Ø20	2-legged @300 mm
	Floors 5 to Roof	400 × 400	4Ø16	12Ø16	2-legged @240 mm

4 Segmentation of the case study

The initial step in the methodology entailed the evaluation of the case study's capacity to 'naturally' segment during collapse scenarios through the initial failure hierarchy verification. This verification was unsuccessful, as it was observed that the maximum load transferable by the floor systems was sufficient to generate propagation of failures.

The second step involved the search for CIDS, a key parameter for the subsequent definition of segment sizes. In order to identify the required scenario, a series of nonlinear dynamic analyses were performed concerning different scenarios of column removal of the sample building. The Applied Element Method (AEM) [15] was adopted to perform the numerical simulations. The isometric view of the AEM model adopted is shown in Figure 2a. As outlined in Section 3, the building was specifically designed to withstand the failure of one column. Therefore, all simulations performed included initial damage scenarios involving the sudden removal of two or more columns. The performed simulations showed that the simultaneous removal of two interior columns was an initial damage scenario severe enough to generate a propagation of failure until total structural collapse.

The third step of the process entailed the delineation of an appropriate segmentation pattern. In accordance with the extension of the CIDS, the influence area of which was considered to be equal to 6 bays, and the axioms of optimal size, location and symmetry described in section 2, the solution shown in Figure 2b was adopted.

Further information on the application of the framework for the segmentation of the case study can be found in [12].

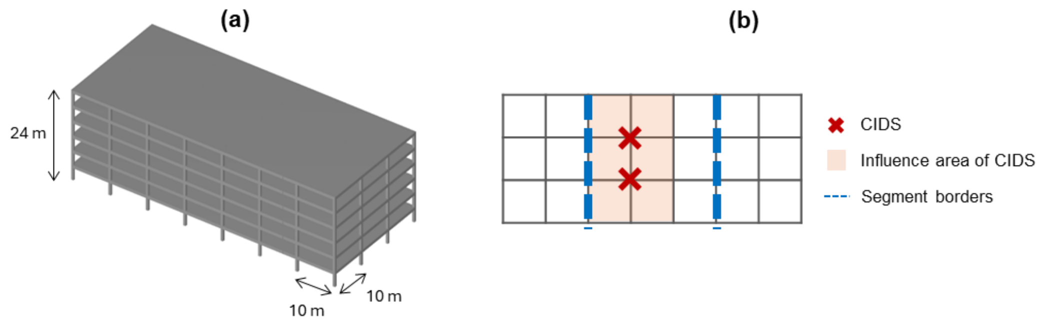

Figure 2. (a) Isometric view of the AEM model of the case study adopted for the numerical simulations. (b) Proposed segmentation pattern of the case study.

5 Cost-benefit analysis of the segmentation configuration

The fourth step of the proposed methodology concerns the evaluation of the cost-effectiveness of the segmentation configuration identified in Section 4. As outlined in Section 2, the probability of structural damage occurring and the cost of implementing segmentation are considered independent parameters, with the implementation of a break-even strategy reflected by Equation 3.

To estimate $P[C|D]$ for the unsegmented (NS) configurations, a numerical non-linear dynamic simulation campaign was performed using the Extreme Loading for Structures (ELS) software, which adopts the AEM for its analysis. In the context of the present study, a series of scenarios was considered in which the load-bearing capacity of two columns was suddenly lost. This choice was motivated by the fact that, given the case study was explicitly designed to withstand the removal of one column, this type of failure scenario was considered not relevant. Conversely, scenarios involving a greater number of columns were deemed less probable. Given the impracticality of conducting a comprehensive evaluation of all potential failure scenarios involving initial two-column failure, a subset of these scenarios was methodically identified according to the following criteria: (i) only scenarios involving column-loss from the ground floor were considered; (ii) only scenarios involving adjacent columns were considered; (iii) the scenarios were identified with a view to taking into account the spatial variability of the considered columns in terms of boundary conditions; (iv) the symmetry of the case study (and, consequently, the number of scenarios symmetrically equivalent to the ones actually performed) was considered when estimating the frequency of occurrence of a given final collapse state. A series of nine two-column removal scenarios were simulated and the results are summarised in Table 3.

Table 3. Summary of the final collapse state observed in the simulation performed for the NS configuration.

Final collapse area	*No. of cases*	*No. of cases symm. equivalent*	*Frequency of occurrence*
0%	6	16	0.62
33%	1	2	0.08
100%	2	8	0.31

In the absence of detailed information regarding the specific design of segment borders, it was hypothesised that segmentation functioned as intended for segmented (S) configurations. Consequently, the collapse area in the segmented building for each scenario was estimated directly from the outcome of the corresponding simulation of the unsegmented building. This was done under the assumption that a segment border was always able to arrest failure propagation, isolating the collapse mechanism within the segment in which it originated. The estimated collapse states for the S configurations are summarized in Table 4.

Table 4. Summary of the final collapse state observed in the simulation performed for the S configuration.

Final collapse area	*No. of cases*	*No. of cases symm. equivalent*	*Frequency of occurrence*
0%	6	16	0.62
29%	3	10	0.38

For each collapse area magnitude observed in both the NS and S configurations, the losses were estimated. In the context of this case study, the focus was exclusively on fatalities in order to estimate losses. This was due to the difficulty of estimating indirect losses (e.g. psychological damage, economic consequences at a regional scale, loss of reputation, among others [16]) and the fact that in previous research [13] it was observed that a loss function considering direct losses (such as fatalities, building reconstruction costs, environmental impacts, among others [16]) is strongly dominated by the fatality parameter. The following formulation, developed by Coburn et al. [17], was adopted to estimate the expected fatalities N_F given a collapse state:

$$N_F = \mathrm{K}_{max} \cdot [M_2 \cdot M_3 \cdot (M_4 + M_5)] \tag{4}$$

where K_{max} is the maximum occupancy in the entire structure (expressed in number of individuals), M_2 is the proportion of people present at the time of collapse, M_3 is the proportion of occupants trapped in the collapsed area, M_4 is the proportion of instant fatalities among trapped occupants, and M_5 is the proportion of delayed fatalities post-collapse. In order to convert the number of fatalities obtained for each collapse state in monetary terms, the number was then multiplied by a Value of Statistical Life, set equal to USD 6 million per individual. This value was selected in accordance with the VSL recommended by the OECD [18] for EU member states was adopted, after adjustment for inflation.

Finally, in order to facilitate the comparability of the obtained results with other probabilities of occurrence of specific hazards, the break-even P_D was divided by three different $P[D|H]$ values, equal to 0.01, 0.05 and 0.10, respectively. The following equation, derived from Equation 3, was used:

$$P[H]_{BE} = \frac{1}{P[D|H]} \times \frac{Cost}{P[C|D]_{NS} \times Loss_{NS} - P[C|D]_S \times Loss_S} \tag{5}$$

The obtained results are summarized in Figure 3. Assuming the implementation cost is on average 230 USD/year (obtained from the mean manufacturing cost estimated in Spain for reducing slab reinforcements in a band thickness 20-50 cm), it can be observed that the segmentation solution in Section 4 would be cost-effective for threats with a probability of occurrence similar (or larger) to that of a bombing attack on critical facilities.

Furthermore, two sensitivity variations were considered for the CBA methodology. Specifically, the following were considered: (i) a reduced VSL (set at USD 1 million) and (ii) the introduction of an Efficiency Index in the estimation of the collapsed areas for the S configurations, under the assumption that failure propagation beyond the segment border could be reduced by 50% with respect to the NS configurations. The comparison between the break-even $P[H]$ curves of the two variations under consideration and that of the reference case, as illustrated in Figure 4, demonstrates that, despite a slight (and expected) reduction in the cost-effectiveness area above the curves, the validity of the results obtained for the reference case is confirmed. In particular, the proposed solution was found to be cost-effective for threats with a probability of occurrence equal to or greater than 1×10^{-4}.

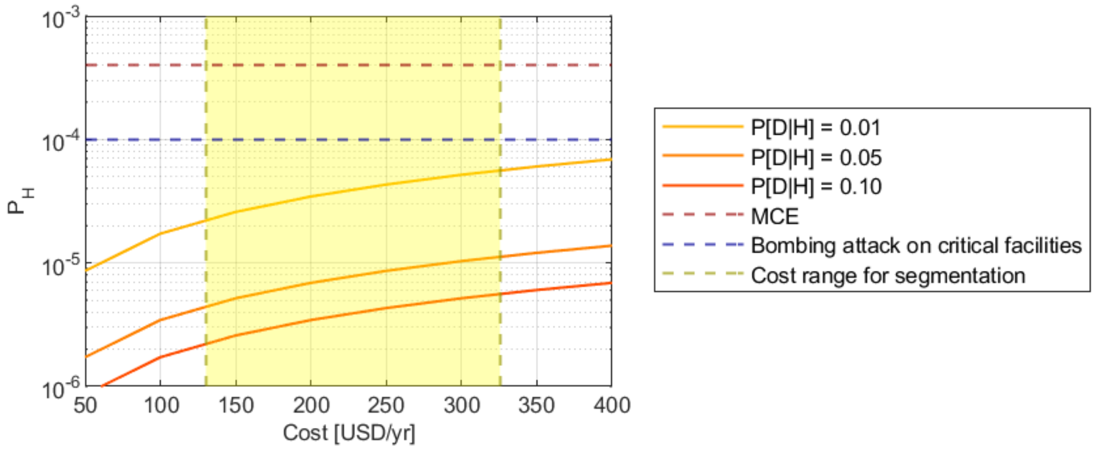

Figure 3. Break-even hazard probabilities $P[H]$ estimated for 2-column removal scenarios, and comparison with the probability of occurrence of a maximum considered earthquake [19] and a bombing attack on critical facilities [20].

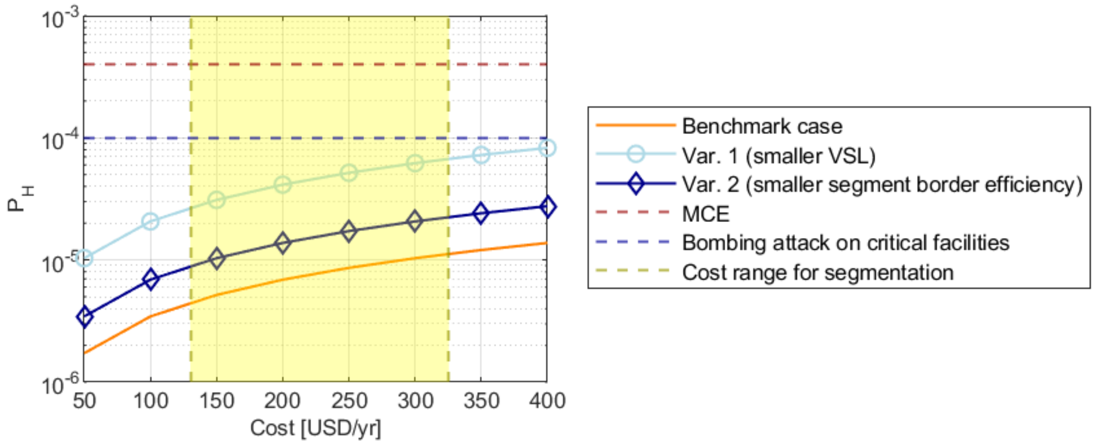

Figure 4. Benchmark case break-even hazard probability $P[H]$ for conditional probability of damage $P[D|H] = 0.05$, and comparison with variations: assuming a smaller VSL (variation 1); assuming smaller segment border efficiency (variation 2).

6 Conclusions

This manuscript delineates a pioneering performance-based methodology for enhancing the structural robustness of buildings. The strategy is founded upon the utilisation of segmentation as a design technique, with the objective of mitigating the risk of disproportionate collapse. In the initial phase, the optimal segmentation configuration for the case under study is identified, based on structural and geometrical criteria. The subsequent phase involves conducting a cost-benefit analysis of the proposed configuration, with the objective of evaluating its cost-effectiveness in comparison to the expected collapse risk reduction. To this end, a case study was identified to test the proposed methodology. The application of this approach to a practical case showed that the identified segmentation configuration can be cost effective for the case studied, for a threat with a probability of occurrence similar to (or greater than) the probability of occurrence of a bomb attack on critical facilities.

However, it is important to highlight that risk assessment is inevitably a highly case-specific process. Consequently, it is imperative to meticulously evaluate the scenarios encompassed in the analysis and all the parameters necessary for estimating consequences, in order to reliably assess the cost-effectiveness of segmentation for diverse building types.

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References

[1] Department of Defense (DoD). UFC 4-023-03. Design of buildings to resist progressive collapse. 2016.

[2] European Committee for Standardization (CEN). EN 1991-1-7. Eurocode 1: Actions on structures. Part 1-7: General actions - Accidental actions . 2006.

[3] GSA (General Services Administration). Alternate path analysis & design guidelines for progressive collapse resistance. General Services Administration 2013.

[4] Starossek U. Current codification. Progressive Collapse of Structures, ICE Publishing; 2017, p. 167–94. https://doi.org/10.1680/pcos.61682.167.

[5] Loizeaux M, Osborn AE. Progressive Collapse—An Implosion Contractor's Stock in Trade. Journal of Performance of Constructed Facilities 2006;20:391–402. https://doi.org/10.1061/(ASCE)0887-3828(2006)20:4(391).

[6] Starossek U. Typology of progressive collapse. Eng Struct 2007;29:2302–7. https://doi.org/10.1016/j.engstruct.2006.11.025.

[7] Starossek U. Design methods. Progressive Collapse of Structures, ICE Publishing; 2017, p. 61–128. https://doi.org/10.1680/pcos.61682.061.

[8] Building Resilient - UPV - ICITECH. Endure. Https://B-ResilientWebsUpvEs/Endure-Home/ 2024.

[9] Makoond N, Setiawan A, Buitrago M, Adam JM. Arresting failure propagation in buildings through collapse isolation. Nature 2024;629:592–6. https://doi.org/10.1038/s41586-024-07268-5.

[10] Faber MH, Stewart MG. Risk assessment for civil engineering facilities: critical overview and discussion. Reliab Eng Syst Saf 2003;80:173–84. https://doi.org/10.1016/S0951-8320(03)00027-9.

[11] Beck AT, Ribeiro L da R, Valdebenito M. Risk-based cost-benefit analysis of frame structures considering progressive collapse under column removal scenarios. Eng Struct 2020;225:111295. https://doi.org/10.1016/j.engstruct.2020.111295.

[12] Caredda G, Makoond N, Buitrago M, Sagaseta J, Chryssanthopoulos M, Adam JM. Enhancing building robustness through a fuse-based segmentation framework. Developments in the Built Environment 2024;19:100515. https://doi.org/10.1016/j.dibe.2024.100515.
[13] Caredda G, Makoond N, Sagaseta J, Chryssanthopoulos M, Stewart MG, Adam JM. Analysing the cost-effectiveness of improving building robustness through segmentation. Submitted for Consideration in Engineering Structures 2025.
[14] European Committee for Standardization (CEN). EN 1991-1-1. Eurocode 1: Actions on structures. Part 1-1: Densities, self-weight, imposed loads for buildings. 2003.
[15] Meguro K, Tagel-Din H. Applied Element Method for structural analysis. Doboku Gakkai Ronbunshu 2000;2000:31–45. https://doi.org/10.2208/jscej.2000.647_31.
[16] Janssens V, O'Dwyer DW, Chryssanthopoulos MK. Assessing the Consequences of Building Failures. Structural Engineering International 2012;22:99–104. https://doi.org/10.2749/101686612X13216060213473.
[17] Coburn AW, Spence RJS, Pomonis A. Factors determining human casualty levels in earthquakes: mortality prediction in building collapse. 10th World Conference on Earthquake Engineering (10WCEE), Madrid, Spain, 1992.
[18] Organisation for Economic Co-operation and Development (OECD). Mortality Risk Valuation in Environment, Health and Transport Policies. Paris: OECD Publishing; 2012. https://doi.org/10.1787/9789264130807-en.
[19] American Society of Civil Engineers (ASCE). Minimum Design Loads and Associated Criteria for Buildings and Other Structures. Reston, VA: American Society of Civil Engineers; 2021. https://doi.org/10.1061/9780784415788.
[20] National Institute of Standards and Technology (NIST). NISTIR 7396: Best Practices for Reducing the Potential for Progressive Collapse in Buildings. NIST; 2007.