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Corner-column failure scenarios in building structures: current knowledge and future prospects

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Abstract

Over the past few decades, increasing awareness of the need for more resilient infrastructure has led to a great increase in the amount of research being performed on the progressive collapse and structural robustness of buildings. Due to their widespread use, much of this research has focused on framed structures. Given the important role of columns in this type of structure, the analysis of the effect of their failure on structural systems has emerged as one of the most useful tools for studying structural robustness. However, the majority of such studies have focused on the removal of internal or edge columns rather than corner columns, which are in principle more vulnerable in many aspects. Although this situation suggests that more research may be needed to improve our understanding in this regard, the large amount of research performed in the field of progressive collapse means that it can be challenging to identify and prioritise the most important research needs. This review article aims to address this challenge through a comprehensive overview and analysis of past research involving corner-column failure scenarios in cast-in-place reinforced concrete (RC), precast concrete, and steel framed buildings. This analysis has made it possible to establish the most important research findings on corner-column failures, to define the limitations of what has been done so far, and to identify the most significant gaps in knowledge to be prioritised by future research.

Keywords: extreme events, progressive collapse, concrete structures, steel structures, robustness, corner columns.

1. Introduction

Progressive collapse in a building structure is defined as the propagation of initial local damage to other parts of the structural system, often leading to a final collapse configuration which is disproportionate compared to the initial damaging event. Despite being a relatively rare phenomenon, the financial and human losses caused by progressive collapse can be disastrous [1,2]. There exist several examples of progressive collapse of building structures, including that of the Ronan Point tower (London, 1968), of the A.P. Murrah Federal Building (Oklahoma, 1995), and of the Champlain towers (Miami, 2021).

The aforementioned partial collapse of the Ronan Point tower triggered a surge in awareness on the need to design structures that are insensitive to localised initial damage, a property that came to be known as structural robustness. As a consequence, the first requirements for enhanced structural continuity were included in building codes in the form of prescriptive design rules [3,4]. Since then, further research in the field has led to the development of a number of structural robustness requirements and design or analysis methods that are now included in building codes and guidelines such as UFC-4-023-03 [5] and EN1991-1-7 [6]. A comprehensive overview of structural robustness requirements in current building codes and of some of the most widely used analysis methods such as the alternative load path method can be found in [2,7]. It is worth noting that the past two decades has been marked by growing research interest on progressive collapse, as evidenced by the significant rise in the yearly number of journal papers published on the topic, from rates that were consistently less than 10 papers/year before 2001 to more than 120 papers published in 2017 alone [2]. In fact, research on progressive collapse is still currently very active [2,8] and there is an ongoing professional effort to improve regulations that address it. As a result, new design guidance documents are also currently under development, notably the upcoming SEI/ASCE disproportionate collapse mitigation standard [9].

Over the years, most of the research that has been performed on the structural robustness of buildings has been based on experimental testing and numerical or analytical modelling, often combining both to draw meaningful conclusions on structural response in extreme or abnormal scenarios. Although most experimental testing up to the present time has been performed on subassemblies consisting of beams, columns, and sometimes slabs, there are also some examples of tests performed on purposely built complete buildings or on existing ones scheduled for demolition [2,10]. Such tests are undoubtedly an invaluable source of information for better understanding secondary resisting mechanisms and for evaluating the effectiveness of proposed solutions for enhancing structural robustness. However, experimental testing tends to be very costly and can rarely be used to evaluate all scenarios of interest in a particular research endeavour. As such, great advancements in structural robustness have also been made by using suitably validated models to simulate and study different scenarios of interest. Models of different complexity have been used for this purpose, including simplified analytical representations of structural systems and more advanced numerical models that can be used to perform simulations of the expected structural response. The latter can be based on the finite element method (FEM), the discrete element method (DEM), the applied element method (AEM), or the cohesive element method (CEM) [2].

It should be mentioned that most of the research carried out on the progressive collapse of buildings concerns framed structures [11], in particular those made of reinforced concrete (RC) and/or steel. This is most likely due to the widespread use of these forms of construction and can be appreciated by examining the number of journal articles that have been published on the progressive collapse of buildings over the years. As shown in Figure 1**,** from a total of 564 journal articles on progressive collapse found in the SCOPUS database, approximately 94% were focused on these types of structural systems. Considering the load paths through which framed structures resist imposed loads, columns represent one of the most critical components for structural stability. As a result, the removal of these vertical load-bearing components has become one of the most widely used approaches for studying progressive collapse and structural robustness.

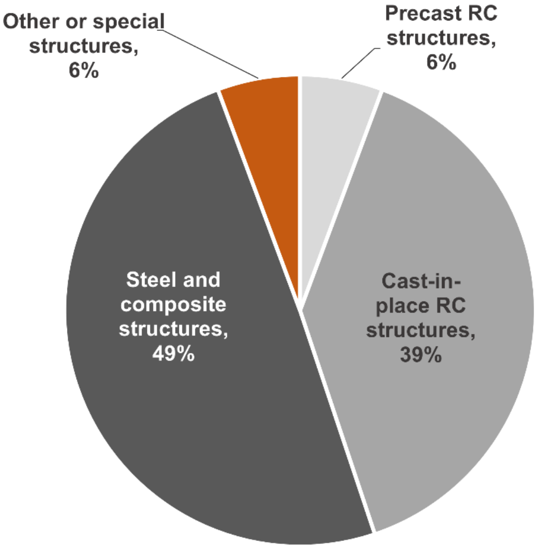


Figure 1. Distribution based on structural typology of 564 journal articles on the progressive collapse of buildings found in the SCOPUS database. The search was limited to journal articles in the engineering subject area and articles were only retained if all the following search terms were included in the title, abstract, or keywords: *progressive collapse, structure, building*.

Given that columns placed at different locations in a building floor plan are effectively characterised by different loading and constraints, the response of a structural system after the loss of these different columns can naturally also be expected to differ significantly. This is in fact why the direct design approach known as the Alternate Load Path method included in UFC-4-023-03 [5] explicitly states different unique column removal locations that a building (of a particular risk category) should be designed to withstand. These unique column-removal locations include the corner column as well as different edge and internal columns. In this regard, it is worth mentioning that far more research has been performed on the removal of internal or edge columns when compared to research on the removal of corner columns. This is particularly true when considering experimental research and can most probably be attributed to the fact that it is generally far more straightforward to design appropriate constraints on a subassembly to reproduce the boundary conditions of an internal or edge column compared to what is required for testing a corner-column removal scenario. As summarised in Figure 2, this state of affairs is also made evident by the results of a search for journal articles on progressive collapse indexed in the SCOPUS database.

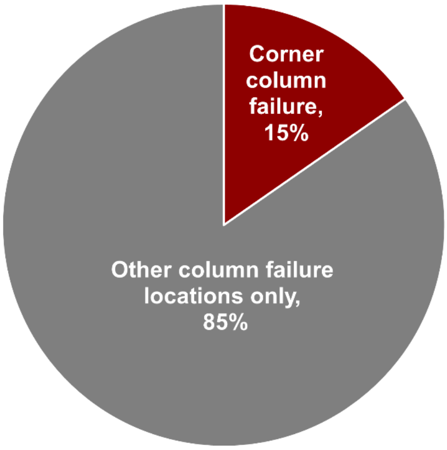


Figure 2. Proportion of 437 journal articles studying column failures that consider corner columns. The search in the SCOPUS database was limited to journal articles in the engineering subject area and articles were only retained if all the following search terms were included in the title, abstract, or keywords: *progressive collapse, structure, building, column*.

Despite having been less studied, corner columns are arguably one of the most exposed and vulnerable structural components in a building. Compared to interior columns, it is often more difficult to protect corner columns from explosions or impacts. In addition, less secondary resisting mechanisms are usually able to develop after the removal of corner columns due to reduced horizontal constraint provided by surrounding elements [12,13]. Therefore, an initial failure involving the loss of a corner column will usually have a higher probability of occurrence. However, compared to disproportionate failures caused by the loss of edge or interior columns, failure propagation after losing a corner column occurs predominantly in the vertical direction, thus limiting the final extent of collapse to the area surrounding the corner span. On the other hand, in cases of edge or interior column failures, collapses usually have significant failure propagation components in both vertical and horizontal directions. In other words, corner-column failures typically have a higher probability of occurrence but result in less consequences, while the failure of edge or interior columns are less likely to occur but result in greater consequences. These characteristics balance the risk of structural failure associated to any type of column in a building. As such, it appears that more research is required to better understand the response of framed structures after the loss of corner columns and on how to mitigate failure propagation in such situations.

Given the high volume of research performed around the world in the field of progressive collapse, obtaining a holistic view of the current state-of-the-art and identifying the most important specific research needs with respect to structural response after corner-column loss is no straightforward task. There do exist several excellent reviews covering previous research, design, and regulatory aspects of progressive collapse [2,4,11,14–16], as well as some focusing only on experimental studies [17–20] or computational simulations [21,22]. Nevertheless, none of them address the specific issue of corner-column failure. This review article thus aims to fill this gap by providing a comprehensive overview of all previous research involving the removal of corner columns for studying progressive collapse. In doing so, it is meant to help researchers and practitioners grasp key aspects of past research findings and identify priorities for future studies.

The systematic process followed for performing the review is first presented along with some key descriptive statistics that provide an overview of the nature of research found on the topic (Section 2). The main findings are then described in separate sections relating to cast-in-place concrete structures (Section 3), precast concrete structures (Section 4), and steel structures (Section 5). This analysis has made it possible to provide an overview of the current state-of-the-art, to define the limitations of what has been done so far, and to identify gaps in knowledge that need to be addressed by future research. These aspects are discussed in Section 6 before finally summarising the main conclusions of this review.

2. Systematic review process & descriptive statistics

The first step of the review process involved performing systematic searches for relevant documents in the SCOPUS database using specific search terms that had to be present in the title, abstract, or keywords. Journal and conference articles as well as book chapters were included in each search, which was limited to documents written in English. The search terms *corner column* and *progressive collapse* were used for all the searches along with additional search terms for each specific type of structure considered within the scope of this review. For cast-in-place RC buildings, a search was performed with *reinforced concrete* or *RC* as additional term. For precast concrete buildings, a search was performed with *precast* or *prefabricated* as additional term, while for steel/composite buildings, a search was performed with *steel* as additional term.

Irrelevant documents were then discarded from those retained after the systematic search. This mostly included research related to types of structures outside the scope of this review, research involving only the removal of internal or edge columns, and research investigating local effects on a column due to specific threats such as blasts, impacts, or fires. Any existing duplicates were eliminated and some additional articles that were known to the authors but did not appear in the SCOPUS search results were added to the final list of references to be considered. After this process, a total of 151 references were retained to be studied for this review, including 91 for cast-in-place concrete structures, 5 for precast concrete structures, and 55 for steel structures. While it is not possible to establish exactly what proportion of all documents ever written on corner-column failures were studied as part of this review, the systematic search process employed does at least ensure that all impactful scientific articles meeting minimum quality criteria were considered.

It is worth noting that the 151 references selected through the previously described systematic process were all published between 2007 and September 2022, which is when the search was performed. As these documents were analysed, key information on the nature of the performed research was systematically collected. This included methods used for analytical or numerical modelling and the type of experimental tests performed when applicable. This detailed information is available in the summary tables included in the following sections, which also include a brief description of the main contribution and findings for each study. A more interactive version of these tables has also been made available at 10.5281/zenodo.7606906 to facilitate searching and filtering the reviewed articles and to allow quickly accessing the original articles using hyperlinks.

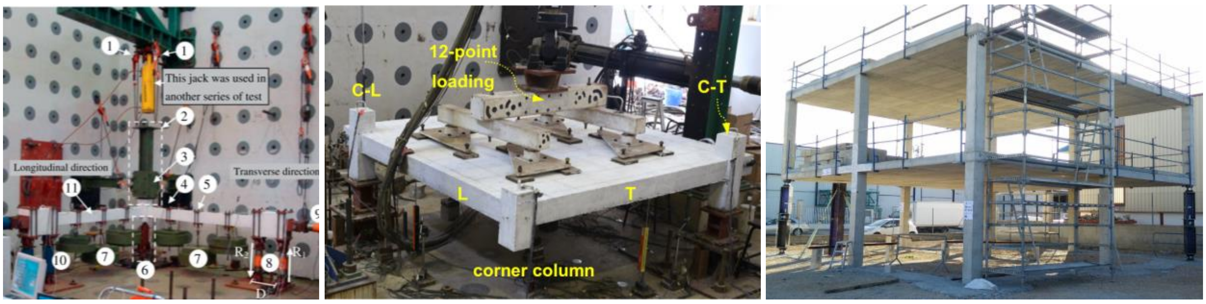
The number of citations to each of the references considered in this review according to the SCOPUS database was also recorded since it can often serve as a useful metric when assessing research impact. Some key measures of central tendency and dispersion among the number of citations to documents on corner-column failures are summarised in Table 1.

Table 1. Descriptive statistics on the number of citations up to September 2022 to documents considered for the review.

	Number of citations		
	Cast-in-place RC	**Steel**	**Precast RC**
Mean	17	18	4
Standard deviation	35	42	3
Median	3	4	5
1st Quartile	1	1	0
2nd Quartile	17	12	6
Maximum	184	220	7

While there are too few studies (only 5) on corner-column failures in precast RC structures to draw meaningful conclusions from descriptive statistics, a relevant observation that can be made for both cast-in-place RC and steel structures refer to the significant differences between the mean and median number of citations. This indicates that the distribution of the number of citations is highly skewed with a small proportion of outliers influencing the mean. In such cases, the median is a better measure of the actual general central tendency. Therefore, the statistics summarised in Table 1 show that although there have been a few very highly cited documents addressing corner-column failures in cast-in-place and steel structures, the vast majority of existing research on the topic has not been referred to by other works. This highlights the need for this review and its potential usefulness.

Previous studies were classified as consisting of only analytical or numerical modelling, only experimental testing, or as consisting of both. In addition, they were also categorised in terms of whether they were based on studying the response of subassemblies or of complete buildings (see Figure 3). For experimental tests, any specimen conceived as being part of a larger structure and requiring specific imposed boundary conditions to simulate its interaction with the rest of the structure was considered as a subassembly (e.g. 2D or 3D frames, or specimens with only beams and beam-column joints). Any specimen consisting of a complete structural system without requiring additional imposed boundary conditions was considered as a building structure. The number of past studies found on cast-in-place RC and steel structures in each category is shown in Figure 4. This distribution is not shown for precast concrete structures since no study on this structural type could be found which included experimental results from a corner-column removal test. As such, all relevant articles on precast concrete buildings were considered as being based on numerical modelling alone for the purpose of this review. It should be noted that studies that validated analytical or numerical modelling strategies using results from an experimental campaign that has already been presented in a past publication were considered as being analytical/numerical only. In such cases, only the first publication presenting the experimental results was considered as having a novel experimental component. Naturally, only experiments involving corner-column failure were considered as being experimental for the purpose of this review. It should be mentioned that the total number of studies on cast-in-place RC structures included in Figure 4 only amounts to 90, even if 91 references were considered for the review. This is because one of the articles, in which no analytical or numerical modelling is presented, is also based on the same experiment presented in another publication. Despite this, the article not considered in Figure 4 was still included in the review because it provides different conceptual analysis.



(a) (b) (c)

Figure 3. Examples of tests on subassemblies (a; b) or building structures (c) for cast-in-place RC. Subfigures (a) and (b) are courtesy of [23] and [24], respectively. Subfigure (c) is part of the study carried out by Adam et al. [10].

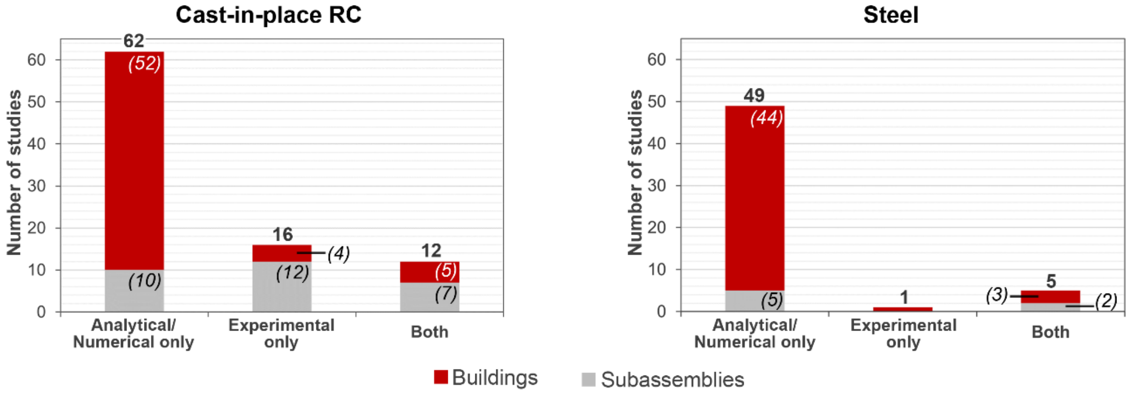


Figure 4. General approaches employed for studying progressive collapse of cast-in-place RC and steel framed structures after corner-column failure. The number of studies in each category are also shown.

As can be seen from Figure 4, there is a far greater number of research works for both structural types based on analytical or numerical modelling compared to experimental ones. This is of course expected due to the significant costs associated to executing an experimental campaign. Another expected observation is that the vast majority of studies using only analytical or numerical modelling consider complete building structures instead of subassemblies. In many of these cases, simulations are used to compare different initial failure scenarios of interest, often in an attempt to identify the most critical ones. For cast-in-place RC structures, the majority of studies that include an experimental component involved subassemblies instead of complete buildings. This must be due to the fact that, under most circumstances, it is significantly less costly and more feasible to test subassemblies compared to complete buildings. Nevertheless, it is important to highlight that tests on subassemblies typically rely on strong assumptions on the boundary conditions imposed on part of a structure [25]. Since these conditions may differ significantly in a real complete structural system, particularly during abnormal loading situations, it can be difficult to reliably ensure that conclusions drawn from an experimental study on subassemblies are applicable to more general cases. Although the same trend concerning subassemblies was not observed in the case of steel structures, too few studies consisting of an experimental component were found for this structural typology (only 6) to identify any meaningful general trends.

Concerning experimental studies, an important aspect that needs to be given appropriate consideration is the scale of the specimens tested with respect to real structures. The distribution of experimental works on corner-column failures according to the scale of the specimen(s) used is shown in Figure 5. It should be noted that the total number of experimental studies on cast-in-place RC structures included in Figure 4 is 28 while the total included in Figure 5 is 27. This discrepancy exists because one of the articles describing a test on a complete building structure [26] did not explicitly mention its scale in comparison to a full-scale structure. However, given the size of the specimen in that case (3.6 × 2.6 × 2.6 m^3), the scale can effectively be considered as being less than 0.5.

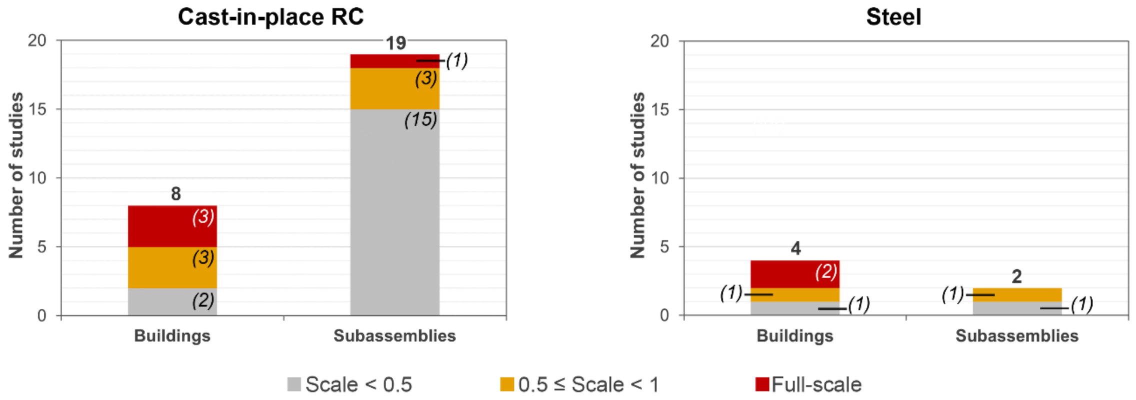


Figure 5. Scales typically used for experimental studies on progressive collapse after corner column failure. The number of studies in each category are also shown.

It is clear to see that significantly more experimental tests of corner-column removal have been performed on cast-in-place RC specimens compared to steel specimens. However, a large number of these tests have been performed on subassemblies with a scale inferior to 0.5. In many of these cases, it may be challenging to properly ascertain the extent of scale effects, which introduces significant doubt on whether conclusions drawn from the tests can be generalised to full-scale structures [27]. As can be seen in Figure 5, only a few tests have been performed on full-scale complete building structures. These tend to be seminal works, such as the articles describing the tests performed on the existing structures of the Hotel San Diego [28] and of the Ohio Union building [29]. The former is the most highly cited document out of all those on cast-in-place RC buildings considered for this review, while the latter is the third most highly cited one out of all those on steel frame buildings. Besides these two cases and another test on an existing steel frame building [30], the remaining two full-scale tests involved a purpose-built cast-in-place RC structure [10,31]. Given the absence of effects due to imposed boundary conditions or scale, it is undeniable that more general conclusions that are directly applicable to other structures may be reliably drawn from the tests on full-scale buildings. Tests on purpose-built structures allow embedded sensors to be placed during construction, an advantage which is particularly important for RC structures, and which allows for improved characterisation of secondary resisting mechanisms that are activated after column loss.

Concerning structural analyses performed to study the response of framed structures after corner-column failure, it was observed that three different types of models are typically used: analytical models or numerical ones based either on the finite element method (FEM) or on the applied element method (AEM). As shown in Figure 6, a very large majority of previous studies have been based on the FEM. Being well-established and widely used, a great variety of FEM-based modelling strategies have been observed for cast-in-place RC and steel structures [21,22], ranging from linear elastic static analysis to nonlinear dynamic ones. It must be said that even though it is not possible to adequately represent many important phenomena of interest using linear elastic analysis, several authors have indeed used it to draw meaningful conclusions, notably by combining simulation results with demand-capacity verifications, often following guidelines prescribed in UFC-4-023-03 [5]. Although the number of studies found concerning corner-column failure in precast concrete buildings (only 5) is too low to derive any general trends, it is interesting to note that most of these studies have been based on the AEM. This could partly be due to the difficulty involved in adequately representing the connections between precast elements using most conventional finite element formulations.

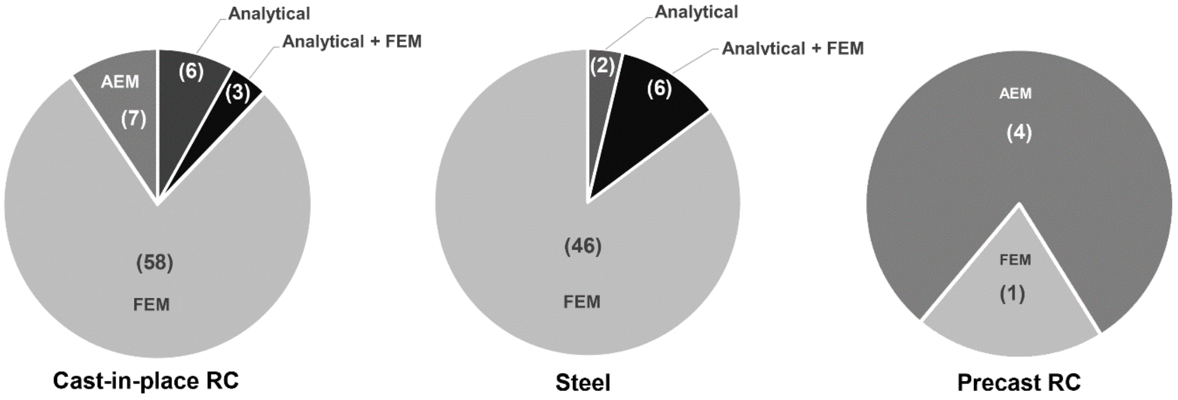


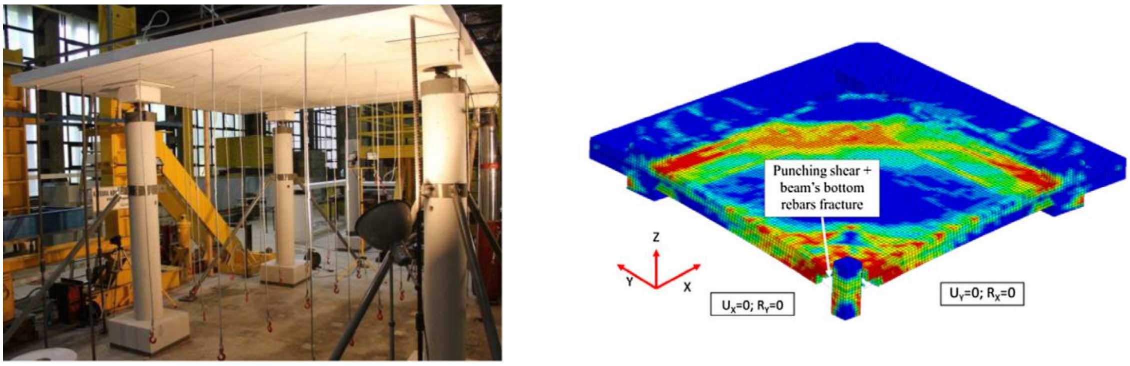
Figure 6. Analytical and numerical methods used to study the progressive collapse of framed structures after corner-column failure. The number of studies in each category are shown in brackets.

Finally, regarding the use of analytical models, it was found that these are typically developed to provide practicing engineers and other researchers with an efficient and fast method for estimating residual capacity and even structural response after column failures. As shown in

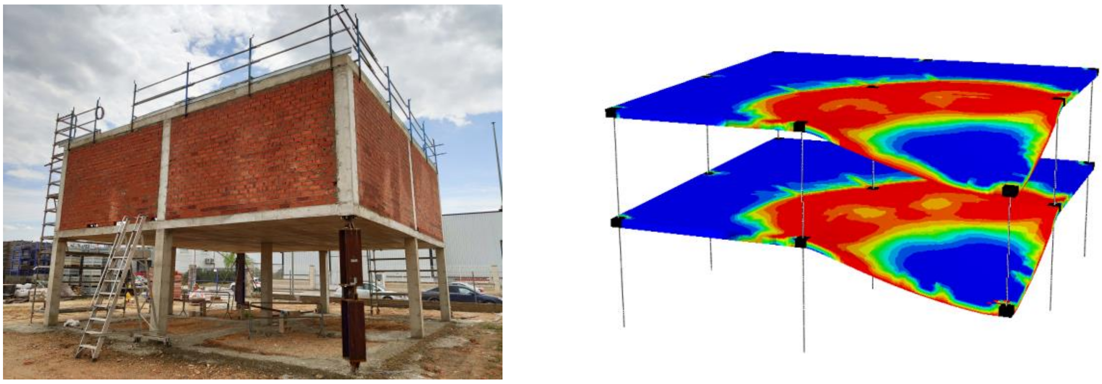
Figure 6, there are several instances where such methods have been used together with FEM-based models, usually for validating their effectiveness. Although many of the proposed analytical models are straightforward to apply, it is important to mention that they are usually based on stronger assumptions compared to some of the numerical modelling strategies, meaning that their applicability is also limited to a smaller set of situations.

3. Corner-column failure in cast-in-place RC structures

This section contains an extensive compilation of progressive collapse research carried out on corner-column failure scenarios for cast-in-place RC structures, including two different approaches based on studying: 1) subassemblies and 2) complete buildings (Figure 7). Some of the most impactful works (evaluated using the number of citations as a metric) are described, while all the references reviewed are included in summary tables (Table 2 and Table 3).



(a) Subassembly - Experimental (b) Subassembly - Numerical



(c) Complete buildings - Experimental (d) Complete buildings - Numerical

Figure 7. Examples of experimental and numerical studies in subassemblies (a; b) and complete buildings (c; d) for cast-in-place RC structures subjected to corner-column failure scenarios. Subfigures (a) and (b) are courtesy of [32] and [24], respectively. Subfigures (c) and (d) are part of the work carried out by Buitrago et al. [31,33].

3.1 Subassemblies

In 2012, Qian and Li [23] investigated the dynamic performance of RC beam-column subassemblies under the corner-column removal scenario. This research included six one-third scale specimens with changes in different parameters. The studied parameters included transverse and longitudinal reinforcement, span length, and span aspect ratio. The authors highlighted that span length significantly affects progressive collapse resistance, and seismically detailed specimens showed more robustness against progressive collapse. In investigating the behaviour of subassemblies in cast-in-place RC structures, the analysis of beams, columns, and slabs without considering the slab effect produces unrealistic results. To fill this gap, the same authors [34] performed six experimental tests on beam-slab subassemblies under the corner column removal scenario to investigate the impact of slabs on RC structures. They examined the force-displacement responses, crack patterns, and fracture modes and showed that considering the concrete slab in the analysis of beam-column substructures can increase the ultimate strength capacity by up to 63% and notably prevent progressive collapse.

In 2013, Qian and Li [35] performed seven one-third scale tests to investigate the influence of transverse reinforcement, seismic or non-seismic design, and beam span ratio on collapse performance. Vierendeel mechanism was identified as a significant resisting action before severe fracture of the corner joint occurred, and then a cantilever beam redistribution action was the dominant effect. Another study of the same authors [36] included tests to understand the effect of drop-panel on response of RC flat-slabs. Flat slabs are more vulnerable to progressive failure compared to structures containing beams and columns because fewer load redistribution mechanisms can be activated. The experimental results showed that considering the effect of drop panels in flat slabs can increase the resistance capacity by 124.7% and significantly prevent progressive collapse. Another article by the same authors [37] reports results of tests performed on 1/3-scale flat slab subassemblies strengthened with Carbon-Fibre-Reinforced Polymer (CFRP), indicating that it is an effective means for improving robustness.

In 2015, Russell et al. [38] performed seven one-third scale tests to investigate the behaviour of RC flat slabs after the sudden removal of a corner, penultimate edge, and internal edge column. The results showed that the flat slab could effectively redistribute the load after removing the column. Shear fracture due to punching was observed due to increased force in the columns adjacent to the eliminated one, but no flexural failure was observed. Deformation in the elastic range in tests under dynamic load was 1.5 times that of elastic deformation in tests under static load. They also showed that Dynamic Amplification Factors (DAFs) are reduced by considering the effects of nonlinear damage. Another interesting conclusion was that the incorporation of the continuous bottom flat-slab reinforcement through the column and increasing the strength of the material did not have a significant impact on the flat-slab behaviour after column removal. In the same year, Qian and Li [39] continued investigating the dynamic behaviour of RC beam-column subassemblies, now both with and without a concrete slab. They compared the results of progressive collapse in the case of the sudden removal of the corner column in these frames with static analysis results, using the definition of load increase factor (LIF; according to UFC 4-023-03 [5]) to investigate the dynamic effects. Results indicated that this factor ranged from 1.30 to 1.34 for the tested specimens.

In 2017, Lim et al. [40] conducted an extensive study which included performing experimental corner-column removal tests on 2/5-scale RC frames both with and without slabs. The tests were employed to study the contribution of catenary action and tensile-membrane action. They concluded that the presence of the slab increased the bending capacity of the frame by about 55%. They also observed that the probability of shear fracture occurring in the corner column removal scenario was low, and that residual load resistance could be attributed mainly to cantilever mechanisms. This last conclusion is perhaps limited, due to the fact that the study was based on subassemblies, in which authors are not considering the contributions of more than one floor. Pham et al. [24] investigated RC substructures under different column removal scenarios. Their main goal was to examine the combination of catenary mechanism effects in beams and tensile membrane mechanism in slabs under two methods of point load and uniformly distributed load. Their results showed that loading affects both the resisting capacity and the deformation and fracture modes. They concluded that the effect of the catenary mechanism in beams is negligible compared to the tensile membrane mechanism.

Already in 2019, Feng et al. [41] investigated the progressive failure behaviour of RC slab-beam substructures strengthened with Glass-Fibre-Reinforced Polymer (GFRP) subjected to corner column failure scenarios. Tests showed that strengthening subassemblies using GFRP increases the resistance of RC slab-beam subassemblies to progressive collapse. Ma et al. [42] presented experimental results for RC flat-slab subassemblies under corner column removal. They studied specimens' fracture and post-fracture behaviours, fracture modes, and resisting mechanisms formed against progressive rupture for two different specimens with and without overhangs. The study showed that these can contribute to reducing the risk of progressive collapse.

Table 2. **Previous progressive collapse research involving cast-in-place RC subassemblies under corner column removal scenarios. The number of citations shown is up to September 2022.**

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Guo et al. (2022) [43]	RC slabs as well as secondary beams can enhance load resistance. Including secondary beams in a design can improve ductility and change the failure mode. Data-driven models based on machine learning are proposed as part of this research to predict the peak resistance capacity of RC structures with slabs and secondary beams.	Yes	FEM	Yes	1/3	-
Qin et al. (2022) [44]	Strengthening schemes aimed at slabs can greatly improve the performance of RC structures against progressive collapse. For the specimens studied, near-surface-mounted (NSM) bars increased the peak capacity more than adding a layer of engineered cementitious composites using the equivalent strengthening quantity of Glass-Fibre-Reinforced polymer (GFRP). A theoretical model for predicting the ultimate capacity of RC structures after corner column failure is also proposed and used to demonstrate that the capacity of flat slab systems is lower than that of beam-column and beam-slab systems.	Yes	Analytical	Yes	1/2	2
Qian et al. (2022) [45]	Of all double-column removal scenarios investigated, the most hazardous one involved the loss of the corner and antepenultimate columns.	Yes	FEM	No	-	3
Qian et al. (2021) [46]	The way in which loads are applied significantly affects overall structural responses, load transfer mechanisms, and failure modes. More significant Vierendeel action developed in the structure under concentrated loading compared to the one under uniformly distributed loading. Load transfer mechanisms that developed in middle storeys differed significantly from those in the top and bottom storeys.	Yes	FEM	No	-	4
Xu et al. (2021) [47]	After corner column removal, flexural actions mainly occurred in the directly affected part while compressive arch action could be observed in the indirectly affected part. The slab was found to contribute greatly to progressive collapse resistance.	No	-	Yes	1/3	-

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Savin et al. (2020) [48]	Propose a physical model and a methodology to study the buckling and fracture of RC moment frames after sudden corner column removal.	Yes	FEM	No	-	5
Du et al. (2020) [49]	In the subassembly tested, no tensile membrane mechanism could be activated in the slab as beams in both directions behaved like cantilevers. The asymmetrical span design was also found to reduce resistance.	No	-	Yes	1/3	4
Prakash & Satyanarayanan (2020) [50]	Experimental results show that infill walls can provide a suitable alternate load path and improve the collapse resistance of RC frames.	No	-	Yes	1/5	3
Feng et al. (2019) [41]	Strengthening with Glass-Fibre-Reinforced Polymer (GFRP) can greatly increase resistance of subassemblies after the loss of a corner column.	Yes	FEM	Yes	1/2	22
Ma et al. (2019) [42]	Torsional strips (spandrel beams) or overhangs can contribute to reducing the risk of progressive collapse. It was shown that yield line theory can be used to estimate slab flexural capacities for corner column removal scenarios.	Yes	Analytical	Yes	1/3	38
Abdelwahed (2019) [51]	An approach for reduced-order modelling of joints is proposed and validated. Based on the cases studied, it was found that for interior and exterior joints, seismic reinforcement detailing is sufficient to resist progressive collapse. However, it is not sufficient in the case of knee joints for which additional vertical stirrups are recommended.	Yes	Analytical, FEM	No	-	3
Pham et al. (2019) [52]	The presence of RC slabs can increase the torsional strength of perimeter beams by as much as 97%.	Yes	FEM	Yes	1	1
Zhang et al. (2018) [53]	An energy-based method for determining the collapse resistance of beam-slab structures subjected to edge or corner column removal is proposed and validated.	Yes	Analytical	No	-	4
Pham et al. (2017) [24]	The way subassemblies are loaded affects the resisting capacity as well as the deformation and fracture modes. Tests performed suggested that the catenary mechanism in beams is negligible compared to the tensile membrane mechanism in slabs.	Yes	FEM	Yes	2/5	66

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Lim (2017) [54]	Slabs can contribute greatly to improving residual capacity. For the concerned specimen, this resulted in an additional capacity of 60%.	Yes	FEM	Yes	2/5	-
Lim et al. (2017) [40]	Slabs can increase the capacity of frames by approximately 55% under corner column removal scenarios.	No	-	Yes	2/5	51
Lim et al. (2017) [55]	The load capacity of the subassembly with an imposed uniformly distributed load was more than 4 times greater than that with an imposed concentrated load. In the latter case, the structure mainly relied on flexural capacity for resisting the imposed loads whereas in the former case compressive arch action in the slab perimeter region and tensile membrane action in the central slab region could also develop.	No	-	Yes	2/5	-
Wieczorek (2016) [56]	Propose a theoretical model for calculating the strength of a corner of a slab-column structure based on interaction graphs of the load capacity.	Yes	Analytical	Yes	1/2	1
Qian & Li (2015) [57]	An analytical model for predicting the load-displacement response after corner column removal is proposed and validated. The model is then employed to evaluate the effect of longitudinal reinforcement ratio as well as beam dimensions and span on the initial stiffness, yield strength, ultimate strength, and residual strength ratio.	Yes	Analytical	No	-	18
Abdelwahed et al. (2015) [58]	Different types of reinforcement anchorage used in knee beam-column joints have significant effects on shear capacity, load-deflection characteristics and failure modes. Better inelastic behaviour could be observed with U-shaped anchorage bars compared to 90° hooks and headed bars.	Yes	FEM	No	-	1
Qian & Li (2015) [39]	Dynamic Load Increase Factors for tested specimens ranged between 1.30 and 1.34.	No	-	Yes	1/3	64
Russell et al. (2015) [38]	In flat slab structures, shear fracture due to punching is a typical failure mode after column loss. Within the elastic range, dynamic effects due to sudden column loss can cause deflections to increase by up to 1.5 times those measured in the static case.	No	-	Yes	1/3	37

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Wieczorek (2014) [59]	Propose a theoretical model for estimating the load capacity of a corner of a flat slab structure based on different assumed static equilibrium conditions and failure modes.	Yes	Analytical	Yes	1/2	2
Zhang et al. (2013) [60]	Ultimate resistance of corner joints in RC frames are mainly influenced by the moment carrying capacity of the beam and column ends.	Yes	FEM	No	-	-
Qian & Li (2013) [37]	Strengthening flat slabs with both orthogonally and diagonally bonded Carbon-Fibre-Reinforced Polymer (CFRP) laminates on the top surface is effective in improving progressive collapse resistance.	No	-	Yes	1/3	45
Qian & Li (2013) [35]	Vierendeel mechanism identified as the principal resisting mechanism before fracture of the corner joint. A cantilever beam redistribution mechanism dominated following this damage.	No	-	Yes	1/3	147
Qian & Li (2013) [36]	Drop-panels can greatly increase the resistance capacity of flat-slab structures (by up to 124.7% according to tested specimens) and reduce the likelihood of brittle punching failure from occurring.	No	-	Yes	1/3	68
Wieczorek (2013) [32]	Higher ductility reinforcing steel can contribute significantly to reducing vulnerability to progressive collapse.	No	-	Yes	1/2	9
Qian & Li (2012) [34]	Slabs can increase ultimate resistance capacity by up to 63%.	No	-	Yes	1/3	154
Qian & Li (2012) [23]	Span length can significantly affect progressive collapse and seismically detailed specimens show more robustness.	No	-	Yes	1/3	147

3.2 Building structures

In 2008, Sasani and Sagiroglu [28] investigated the progressive collapse of a six-story real RC building in San Diego under a two-column removal scenario, including a corner column. They analysed the load redistribution mechanism and the change in the axial force of the columns. Bi-directional Vierendeel action was identified as the dominant resisting mechanism, and, although the building lacked integrity, it withstood the failure scenario.

In 2009, Mohamed [61] used different analyses methods based on the FEM to study the response of a RC building after corner-column loss. The results showed the importance of considering three-dimensional effects to account for torsional shear stresses, which was found to be most critical for progressive collapse design in certain situations.

In 2012, Helmy et al. [62] used nonlinear dynamic simulations performed using the AEM to study the response of a typical 10-storey structure designed according to the ACI 318-08 code [63] against several column-loss scenarios, including that of the corner column. They found that the structure did not meet the progressive collapse resistance requirements established in UFC-4-023-03[5]. It is worth noting that another similar study [64] published by the same authors the following year found that the design of RC structures based on ACI 318-08 met the requirements of the GSA code for progressive collapse resistance [65]. The importance of considering the contribution of slabs for achieving a cost-effective design was highlighted in both of these studies.

In 2013, Xiao et al. [66] investigated progressive failure behaviour in a three-story reinforced concrete building with a one-half scale under different scenarios of sudden column removal. Their experiments focused on the change in the load-resisting mechanism during progressive collapse due to column removal, including corner column removal. During experimental tests in the corner column removal scenario, only the elastic response of the structure was observed, and no failure occurred.

The work of Yi et al. [67] published in 2015 presented results of column-removal tests from a 3/7-scale flat slab RC structure. In the case of corner-column removal, the formation of a positive yield line spanning between the two adjacent penultimate columns was observed on the top surface. Test results also revealed that the removal of edge or corner columns was more critical that the removal of an interior column for this case.

In 2016, Xue and Le [68] developed a two-scale numerical model to investigate the probabilistic behaviour of RC buildings under progressive collapse due to column removal. They used this model to examine the behaviour of a ten-story RC building under sudden corner column removal scenarios, using probabilistic and deterministic analysis. The results showed the importance of probabilistic methods for analysing progressive collapse. Still in 2016, Wang et al. [69] conducted an experimental corner-column removal test of a one-third scale framed structure of 2 × 3 bays with two storeys. They observed that the redistribution of loads occurred mainly in components adjacent to the removed column. In this case, their experiments showed that the beam resisting mechanism contributed most to load redistribution and that compressive arch action in frame beams helped to significantly improve the structure's capacity. They also developed a simplified method for obtaining the frame's collapse capacity.

In 2017, Bao et al. [70] developed a computational method based on a reduced-order modelling technique for 3D RC structures to estimate robustness in RC buildings under column removal scenarios (including corner columns). They used an energy-based method to consider the dynamic effects of column removal. They also proposed a criterion for structural robustness based on the normalization of the final capacities of the structure under the column removal scenario.

In 2019, Shan et al. [71] presented results of a parametric study performed using FEM simulations. The study indicated that buildings having the same arrangement in plan but more storeys tend to have greater progressive collapse resistance.

In 2020, Adam et al. [10] published the results of a highly-instrumented full-scale experimental test on a RC building under the corner-column removal scenario. Using the test results, they investigated the structure's dynamic behaviour, analysed the alternative load paths (ALPs) that formed in the system, and computed DAFs based on the difference with results from static analyses performed using the FEM. These test results were also used to calibrate a nonlinear dynamic model and perform a more extensive parametric study [33]. The outcomes of this research could be useful for the development of recommendations against progressive collapse in future design codes. Nyunn et al. [72] performed computational simulations of RC structures to investigate the effect of masonry walls in preventing progressive collapse due to external column removal scenarios, especially corner-column removal. The simulation results showed that masonry walls significantly increase the resistance to progressive failure and have an influential role in redistributing loads.

In 2021, Buitrago et al. [31] investigated the effect of infill walls on progressive collapse resistance based on tests performed on a full-scale RC building with infill walls. The primary purpose of this study was analysing ALPs after the sudden corner-column failure, and to determine DAFs and LIFs in RC buildings accounting for the effects of infill walls.

Table 3. Previous progressive collapse research involving cast-in-place RC buildings under corner column removal scenarios. The number of citations shown is up to September 2022.

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Kumar et al. (2022) [73]	After the removal of a ground floor column, the top ends of adjacent columns are more prone to damage compared to their bottom ends. The failure of the penultimate column was found to be more critical than that of the corner column.	Yes	FEM	No	-	-
Rajendran & Gopalakrishnan (2022) [74]	Removal of columns on the 5th floor can lead to an increase of more than 50% in the axial load.	Yes	FEM	No	-	-
Scalvenzi et al. (2022) [75]	Seismic retrofitting with Carbon-Fibre-Reinforced Polymers (CFRP) can also greatly enhance structural robustness. However, the effectiveness of this enhancement can become insufficient when the beam span length is greater than 5 m.	Yes	FEM	No	-	9
Buitrago et al. (2021) [31]	Provide analyses of alternative load paths (ALPs), dynamic amplification factors (DAFs), and load increase factors (LIFs) for a flat slab structure accounting for effects of infill walls.	Yes	FEM	Yes	1	13
Dmitriev & Lalin (2021) [76]	For the cases studied, linear static and dynamic analysis led to errors in the range of 50-70%, nonlinear static analysis led to errors in the range of 10-400% while nonlinear dynamic analyses proved to be most accurate with a maximum error of 7%.	Yes	FEM	No	-	1
Garg et al. (2021) [77]	For the studied building, adding a perimeter beam, adding shear walls, or doing both were found to reduce maximum displacements by up to 81% while also reducing the demand-capacity ratio of critical columns by up to 67%.	Yes	FEM	No	-	3
Abdulsalam & Chaudhary (2021) [78]	Increasing member cross-sectional dimensions was required to improve progressive collapse performance for the corner column loss scenario while more cost-effective solutions could be derived for interior and edge column loss scenarios.	Yes	FEM	No	-	1
Sheikh et al. (2021) [79]	Displacement controlled analysis methods can lead to more accurate results compared to full loading methods. Based on the 2D analysis performed, adding an additional bay and an additional floor reduced the vertical displacement by 59% in the corner column removal case.	Yes	FEM	No	-	-

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Garzón-Roca et al. (2021) [80]	Proposed a dynamic punching shear model for sudden column removal in flat slab structures.	Yes	Analytical, FEM	No	-	2
Dmitriev et al. (2021) [81]	Applying linear static and linear dynamic analysis procedures can result in large errors with differences in terms of peak and residual displacements of up to 56% and 72% respectively when compared to results of nonlinear dynamic analysis.	Yes	FEM	No	-	2
Ahmed et al. (2021) [82]	Based on the cases studied, the removal of a corner column was found to be more likely to cause progressive collapse compared to the removal of a middle column.	Yes	FEM	No	-	1
Prakash et al. (2021) [83]	Of all the cases studied, the greatest shear force demand-capacity ratios were observed for the removal of a corner column from a bare frame structure (with imposed wall loads) that has an asymmetric vertical configuration with the tallest side above the removed column. Results indicate that failure propagation would not occur for the same case but with infilled frames.	Yes	FEM	No	-	-
Ksenofontova (2021) [84]	For the case studied, failure of the corner column on the ground floor causes the corner of the building to collapse globally.	Yes	FEM	No	-	-
Adam et al. (2020) [10]	Evaluation of alternative load paths (ALPs) and dynamic amplification factors (DAFs) based on the sudden corner column removal of a highly instrumented real-scale building.	Yes	FEM	Yes	1	35
Wieczorek (2020) [85]	There were important differences between predictions of the numerical models employed and those of the concerned experiment. The models still provide a good representation of the observed experimental behaviour in initial stages.	Yes	FEM	Yes	1/2	-
Buitrago et al. (2020) [33]	Extensive parametric study evaluating alternative load paths (ALPs) and dynamic amplification factors (DAFs) to provide design suggestions and recommendations for flat slab structures.	Yes	FEM	No	-	1
Nyunn et al. (2020) [72]	Demonstrate that masonry walls increase resistance to progressive failure.	Yes	FEM	No	-	22
Karimiyan (2020) [86]	Progressive collapse distribution patterns obtained from computational analyses of low-rise and mid-rise buildings are proposed as a tool to predict collapse propagation in structural elements of similar buildings subjected to corner and edge column failure.	Yes	FEM	No	-	-

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Nyunn et al. (2020) [87]	Slabs contribute significantly to load redistribution and to enhancing structural resistance after the loss of a column.	Yes	FEM	No	-	3
Divya & Nikhil (2020) [88]	Failure of the corner column causes more torsional vibration compared to other cases of column loss.	Yes	FEM	No	-	-
Mahrous et al. (2020) [89]	Simulation results indicated that a post-tensioned RC flat slab structure designed according to the ACI 318-14 code satisfied criteria established in UFC 4-023-03 for progressive collapse resistance.	Yes	AEM	No	-	7
Parisi & Scalvenzi (2020) [90]	In the case of sequential column removal, the ratio between removal times plays an important role in determining load capacity.	Yes	FEM	No	-	22
Shan et al. (2019) [71]	The study results show that buildings with more storeys tend to have greater resistance to progressive collapse for the same arrangement in plan. Guidance for comparing the relative robustness of buildings is also provided.	Yes	FEM	No	-	19
Liu et al. (2019) [91]	The extent of axial force redistribution to same-storey columns depends on load magnitude and distance from the removed column.	Yes	FEM	No	-	2
Nassir et al. (2019) [92]	Of all damage scenarios studied, multi-column removal scenarios involving a corner and another exterior column turned out to be most critical.	Yes	FEM	No	-	4
Esfandiari & Latifi (2019) [93]	Results of the analysis performed show that reinforcement with Carbon-Fibre-Reinforced Polymer (CFRP) sheets is an effective way to rehabilitate and reduce progressive collapse risk in RC structures.	Yes	FEM	No	-	9
Abdelwahed (2019) [94]	A greater moment capacity of the joint above the removed column leads to less moment being generated at the beams' other ends.	Yes	FEM	No	-	-
Kuncham & Pasupuleti (2019) [95]	Results indicate that structures are more vulnerable to progressive collapse after corner column removal when compared to middle column removal. For the scenarios studied, it was found that disproportionate collapse is less likely when structures contain more storeys.	Yes	FEM	No	-	-
Kumari (2018) [96]	Results indicate that bays with greater spans are more vulnerable to progressive collapse.	Yes	FEM	No	-	1

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Prakash et al. (2018) [97] Prakash et al. (2018) [98]	Corner column removal was found to have more severe effects on the structure compared to middle column removal.	Yes	FEM	No	-	-
Gowtham et al. (2018) [99]	Corner column removal has a greater potential for progressive collapse compared to middle column removal.	Yes	FEM	No	-	4
Kravchenko et al. (2018) [100]	Several recommendations for the design of high-rise buildings to reduce progressive collapse risk are given based on analysis results.	Yes	FEM	No	-	-
Stathas et al. (2017) [101]	Experimental tests on a complete scaled building demonstrated that infill walls can provide an additional secondary load path and contribute to reducing damage in the event of a column loss. Openings of various sizes did not seem to affect the favourable action of the infill walls.	No	-	Yes	4/5	-
Besoiu & Popa (2017) [102]	Including autoclaved aerated concrete infill walls in the numerical model of a real 13-storey building resulted in a reduction of the maximum predicted vertical displacement above the removed corner column by 48%.	Yes	AEM	No	-	4
La Mazza et al. (2017) [103]	Adopting seismic detailing results in improved structural robustness.	Yes	FEM	No	-	5
Zhang et al. (2017) [104]	Simulation results suggest that a dynamic increase factor (DIF) of 1.8 is suitable for performing static analysis of the removal of a corner column. The DIF in corner column removal scenarios was found to increase as the floor from which the column is removed increases.	Yes	FEM	No	-	-
Attia et al. (2017) [105]	Losing a column in a flat slab system is more critical on upper floors. For the 10-storey building under study, the most critical vertical elements to remove turned out to be a near-corner interior column and an edge shear wall.	Yes	AEM	No	-	9
Shah et al. (2017) [106]	Using energy dissipation devices such as viscoelastic dampers in irregular buildings can contribute to reducing demand-capacity-ratios of adjacent structural members after the loss of a column. For the case analysed, removal of the interior column was found to be more critical than the removal of a corner column.	Yes	FEM	No	-	1
Bao et al. (2017) [70]	Developed a computational methodology for evaluating structural robustness against column removal scenarios and propose a criterion for structural robustness.	Yes	FEM	No	-	35

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Zhou et al. (2016) [26]	Three stages of collapse after corner column failure were identified and defined based on a quasi-static pushdown test: elastic response stage, plastic hinge formation stage, and failure stage.	Yes	FEM	Yes	-[*]	1
Zhang et al. (2016) [107]	Increasing section height and rebar ratio in the lower part of beams increase progressive collapse resistance. The specially shaped columns investigated do not significantly change the progressive collapse resistance and results in a reduction of lateral stiffness.	Yes	FEM	Yes	1/3	4
Wang et al. (2016) [69]	The beam resisting mechanism and compressive arch action can contribute significantly to collapse resistance capacity.	Yes	Analytical, FEM	Yes	1/3	13
Prakash et al. (2016) [108]	Structures with infilled frames have better progressive collapse resistance compared to bare frame structures.	Yes	FEM	No	-	1
Chiranjeevi & Simon (2016) [109]	Although the structure analysed satisfies progressive collapse design requirements established in UFC-4-023-03, plastic hinge formation was found to be more severe for corner column removal compared to interior column removal.	Yes	FEM	No	-	2
Xue & Le (2016) [68]	Demonstrated the importance of probabilistic methods for analysing progressive collapse behaviour.	Yes	FEM	No	-	14
Helmy et al. (2015) [110]	Masonry infill walls play a vital role in preventing progressive collapse in the corner column removal scenario.	Yes	AEM	No	-	12
Yi et al. (2014) [67]	Removal of a corner column from a flat slab structure during a quasi-static experiment led to the formation of a positive yield line on the top surface between the two columns adjacent to the removed one. The removal of an edge or corner column was found to be more critical than the removal of an interior column in this case.	No	-	Yes	3/7	61
Xiao et al. (2013) [66]	The three-storey building tested only exhibited an elastic response after corner column removal and no failure occurred.	No	-	Yes	1	18
Wieczorek (2013) [111]	Adequately arranged reinforcement of considerable ductility can provide additional load capacity due to part of the slab acting as a concave reversed shell.	Yes	FEM	Yes	1/2	8

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[*] Scale not specified (specimen of 3.6 m × 2.6 m × 2.6 m)

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Wang et al. (2013) [112]	Based on the cases studied, applying the simplified tie force method included in UFC 4-023-03 did not significantly improve progressive collapse resistance since they could not be fully activated. On the other hand, it was shown that strengthening the structure with X-type tension cables did improve progressive collapse resistance.	Yes	FEM	No	-	1
Helmy et al. (2013) [64]	For the typical 10-story structure studied, it was found that performing the design according to the ACI 318-08 code resulted in a structure that met the requirements of the GSA guide for progressive collapse resistance. It was also shown that considering the contribution of the slab leads to a more cost-effective design.	Yes	AEM	No	-	17
Pachenari et al. (2013) [113]	The nonlinear static alternative load path procedure described in UFC-4-023-03 was shown to be more conservative than the corresponding nonlinear dynamic procedure. The maximum shear forces in beams estimated using the static procedure were found to be up to 27% greater for the cases analysed.	Yes	FEM	No	-	16
Yu & Li (2013) [114]	For the 24-storey structure analysed, progressive collapse is more likely to occur after failure of an edge column compared to that of a corner shear wall.	Yes	FEM	No	-	-
Hafez et al. (2013) [115]	Demonstrated the capability of the applied element method (AEM) for modelling progressive collapse behaviour.	Yes	AEM	No	-	8
Yagob et al. (2012) [116]	Results of nonlinear dynamic simulations of typical shear wall buildings indicated that progressive collapse would occur in all of the column removal scenarios investigated. The extent of collapse propagation was found to be greater when an interior column is removed.	Yes	FEM	No	-	-
Helmy et al. (2012) [62]	For the typical 10-story structure studied, it was found that performing the design according to the ACI 318-08 code resulted in a structure that did not meet the requirements of UFC-4-023-03 for progressive collapse resistance. It was also shown that considering the contribution of the slab leads to a more cost-effective design.	Yes	AEM	No	-	56
Sun & Lin (2011) [117]	Failure of a column leads to an increase of the maximum interlayer displacement and of the basic natural vibration period while reducing the minimum ratio between shearing force and weight.	Yes	FEM	No	-	1

Authors and year	**Main findings and contribution**	**Analytical or numerical modelling**		**Experimental**		**Cited by (SCOPUS)**
		Yes / No	**Method**	**Yes/No**	**Scale**	
Mohamed (2009) [61]	Three-dimensional analysis is particularly important for the case of corner column removal to account for torsional shear stresses that can control the design.	Yes	FEM	No	-	54
Sasani & Sagiroglu (2008) [28]	Bi-directional Vierendeel action was identified as the dominant resisting mechanism after loss of the corner column.	No	-	Yes	1	184
Mohamed (2007) [118]	Limiting damage in corner panels to thresholds prescribed in building codes and guides can be achieved by adjusting the spans to the exterior columns adjacent to the corner one, by designing steel bracing to support the additional load, by designing the slab and beams to cantilever the full length after column loss, or by stiffening columns for code specified pressure levels.	Yes	FEM	No	-	4

4. Corner column failure scenarios in precast concrete structures.

Given the increasing use of precast concrete structures in recent years, there is undeniably a need to better understand their progressive collapse resistance. However, compared to the numerous experimental and numerical studies conducted on the progressive collapse behaviour of cast-in-place RC structures, very little research has been done on corner-column failure in precast RC buildings. All the relevant studies found are described in this section, and are focused on complete building structures, as can be seen in the example of Figure 8. Table 4 summarizes all the references reviewed.

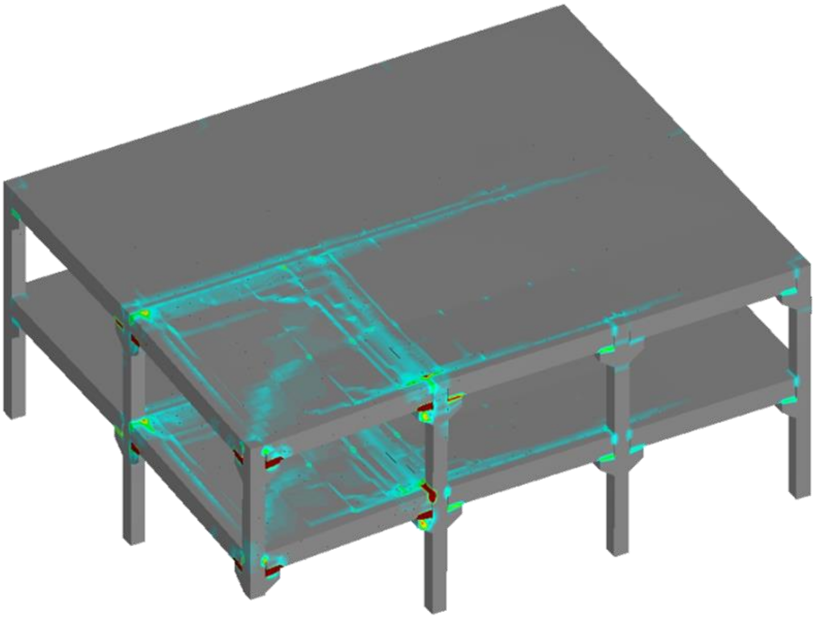


Figure 8. Example of numerical study in complete buildings for precast concrete structures subjected to corner-column failure scenarios carried out by Makoond et al. [119].

In 2020, El-desoqi et al. [120] used the AEM to simulate the removal of different columns (including corner columns) from different precast RC structures. Although the study showed that floor systems with hollow-core slabs can contribute to improving a structure’s ability to resist column removal, it was made clear that adequate connectivity between slabs and beams is crucial for this contribution. Another study based on the AEM performed by Alanani et al. [121] revealed that prestressing can help improve resistance after corner-column failure.

In 2021, Ravasini et al. [122] investigated the robustness of precast RC frame buildings under corner-column and other removal scenarios. Nonlinear analyses performed using the FEM showed that the extent of failure propagation depends strongly on the strength of column-beam joints and tying reinforcement. A simplified modelling approach was also proposed to investigate the progressive collapse of precast RC structures after column removal.

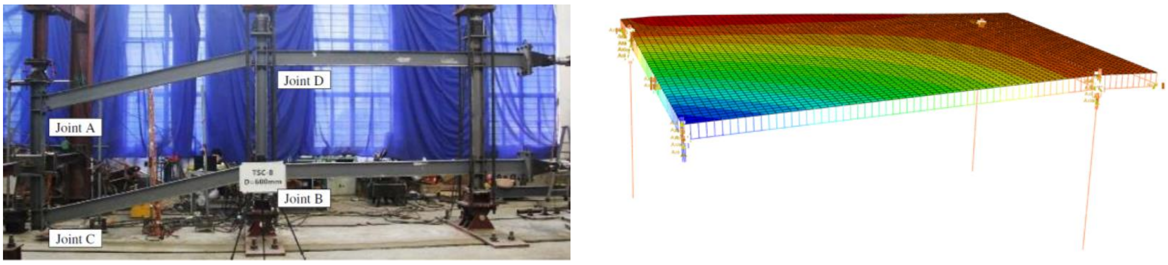
In 2022, Makoond et al. [119] used a numerical model based on the AEM to study the effect of different design options. The modelling strategy was based on calibrating the most uncertain parameters using previous tests on subassemblies available in literature [25] and the base model was built to help plan an experimental campaign on a 2-storey precast building with 3×2 bays. The simulation results presented show the importance of considering system behaviour when performing progressive collapse design.

Table 4. Previous progressive collapse research involving precast RC buildings under corner column removal scenarios. The number of citations shown is up to September 2022.

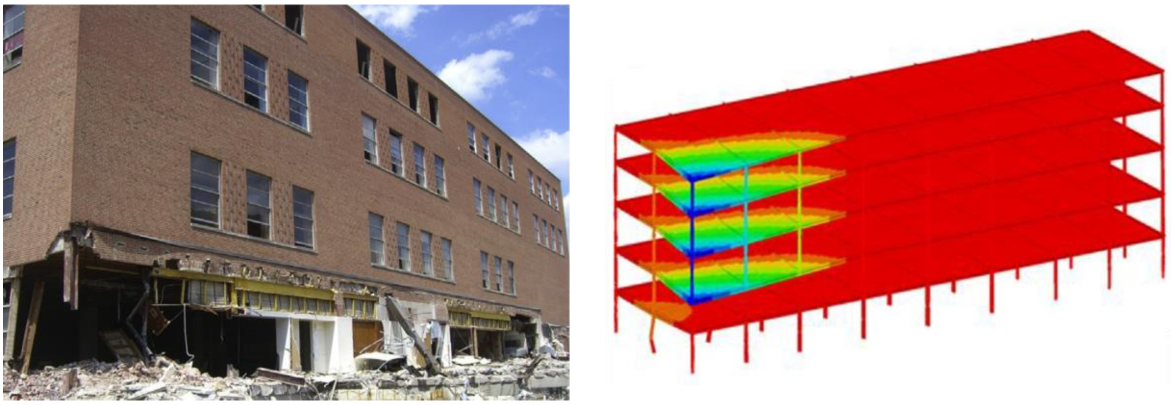
Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Makoond et al. (2022) [119]	Selective strengthening of specific structural members can lead to undesirable load redistribution and to lower global residual load capacity after column loss.	Yes	AEM	No	-	-
Ravasini et al. (2021) [122]	A simplified modelling method for investigating the progressive collapse of precast frame structures was proposed. It was also shown that tying systems in both directions play an important role in achieving an acceptable level of structural robustness	Yes	FEM	No	-	7
Makoond et al. (2021) [25]	Numerical analyses revealed that providing tying reinforcement through specifically designed sleeves in precast columns can provide sufficient robustness to prevent failure propagation after corner and edge column removal.	Yes	AEM	No	-	-
Alanani et al. (2020) [121]	It was shown that the applied element method can be used to efficiently simulate progressive collapse scenarios of interest and that prestressing can help improve the progressive collapse resistance of precast concrete buildings, even when faced with a corner column failure.	Yes	AEM	No	-	6
El-desoqi et al. (2020) [120]	Analysis results revealed that not considering the entire structural system or the contribution of slabs can lead to misleading results and that beams with greater cross section dimension lead to greater compression arching resisting forces.	Yes	AEM	No	-	5

5. Corner column failure scenarios in steel structures.

All the research reviewed on corner-column failures in steel and composite framed buildings is presented in this section. Previous works have been organised in two subsections, one concerning research on subassemblies and the other concerning research on building structures (see Figure 9). These subsections are organised in the same way as those of Section 3 on cast-in-place RC buildings, with the most impactful works described in the main body of the text and all reviewed documents included in summary tables (Table 5 and Table 6).



(a) Subassembly - Experimental (b) Subassembly - Numerical



(c) Complete buildings - Experimental (d) Complete buildings - Numerical

Figure 9. Examples of experimental and numerical studies in subassemblies (a; b) and complete buildings (c; d) for steel structures subjected to corner-column failure scenarios. Subfigures (a), (b), (c) and (d) are courtesy of [123], [124], [29], and [125], respectively.

5.1 Subassemblies

In 2019, Fu and Tan [124] numerically investigated robustness in concrete-steel composite floors under the corner-column removal scenario. A numerical model was calibrated based on a previous internal-column removal experimental test performed on a steel frame-composite floor subassembly. The validated modelling strategy was then employed to perform both static and dynamic simulations of a subassembly in a corner-column removal scenario, which enabled the analysis of dynamic increase factors, load-deformation curves, load transfer mechanisms, and failure modes. It was concluded that loads are mainly resisted by cantilever action of beams and slab after the loss of a corner column, resulting in a more brittle global failure mode compared to internal-column loss. In another article published the same year, Zhang et al. [126] used analytical and numerical methods to investigate the effect of composite slabs on failure modes and resistance mechanisms formed after corner-column removal in subassemblies with beam-column joints. The results showed that the composite slab has a significant effect on improving the behaviour of the structure against progressive collapse. They divided the observed collapse development into four stages: elastic, elastoplastic, plastic, and collapse limit. In the elastic stage, the flexural strength of the composite frame prevented failure, and in the post-elastoplastic stage, catenary and tensile-membrane action were the predominant mechanisms able to prevent progressive collapse.

In 2020, Li et al. [127] employed an analytical model they developed to perform a parametric study on the progressive collapse resistance of multi-storey composite framed structures. The analysis performed allowed them to conclude that Vierendeel action significantly enhances structural capacity after corner-column failure, while catenary action was not found to contribute to resistance.

In 2021, Qian et al. [123] reported results of several tests performed on five half-scale steel frame subassemblies, one of which was designed to study the removal of a corner column. Their analysis also led them to conclude that Vierendeel action contributes significantly to resistance after corner-column failure. They also showed that increasing the thickness of top-and-seat angle connections can increase residual capacity after column removal.

Already in 2022, Kong et al. [128] tested a 1/3-scale three dimensional steel frame-composite floor subassembly under corner-column removal and developed a theoretical model for collapse assessment of this type of structure. They extracted the load-displacement curves, failure modes, and deflection patterns from the test to study corner-column failure on these structural systems and for developing the theoretical model. Regarding the theoretical model, they found enough accuracy but also highlighted its limitations, which should be accounted for in future research.

Table 5. Previous progressive collapse research involving steel and composite subassemblies under corner column removal scenarios. The number of citations shown is up to September 2022.

Authors and year	**Main findings and contribution**	**Analytical or numerical modelling**		**Experimental**		**Cited by (SCOPUS)**
		Yes / No	**Method**	**Yes/No**	**Scale**	
Kong et al. (2022) [128]	Developed a theoretical model for predicting the load-displacement response of 3D composite floor systems up to failure when subjected to a corner column removal.	Yes	Analytical, FEM	Yes	1/3	-
Ghassemieh et al. (2021) [129]	Overall, special moment resisting frames designed for lateral loads have a good resistance to progressive collapse. It was concluded that a structure is more vulnerable to progressive collapse after losing a corner column compared to losing one of its central columns. It is deemed that progressive collapse potential reduces as the number of storeys increase due to reduced beam rotations and ductility demands.	Yes	FEM	No	-	-
Qian et al. (2021) [123]	Flexural action dominated the response of tested bare frames under a corner a corner column loss scenario. The flexural action was significantly enhanced by Vierendeel action. Load-resisting capacity was found to increase significantly when the thickness of top-and-seat angle connections were increased.	Yes	Analytical	Yes	1/2	4
Li et al. (2020) [127]	An analytical method is proposed to predict progressive collapse resistance of multi-storey composite framed structures. It was found that the Vierendeel effect significantly enhances structural resistance after corner-column loss (by more than 60% in some cases). For the same corner-column loss scenarios, no noticeable catenary action developed in steel beams.	Yes	Analytical, FEM	No	-	8
Fu & Tan (2019) [124]	Composite floor systems fail in a less ductile manner in corner column removal scenarios compared to internal column removal scenarios. Dynamic increase factors for the former were found to be greater than those for the latter.	Yes	FEM	No	-	8
Zhang et al. (2019) [126]	Four stages of a progressive collapse in composite frames have been identified and defined: the elastic stage, the elastoplastic stage, the plastic stage, and the collapse-limit stage. It was also concluded that composite slabs have a significant effect on improving progressive collapse resistance.	Yes	Analytical, FEM	No	-	3
Masajedian & Driver (2016) [130]	It was shown that increasing the thickness of the metal deck in composite slabs enhances the overall rotational and loading capacity of the structural system. However, increasing the slab reinforcement did not significantly improve loading capacity after corner column removal.	Yes	FEM	No	-	-

5.2 Building structures

In 2008, Vlassis et al. [131] applied a design-oriented methodology that was presented in a companion paper [132] to study the behaviour of a typical steel-framed composite building after the removal of a peripheral column and a corner column from the ground floor. Their study showed that steel-framed composite structures can be prone to progressive collapse, particularly due to failure of support joints in transferring loads to surrounding undamaged members. In doing so, they highlighted that structural robustness cannot be guaranteed by tying force requirements alone without explicit consideration of ductility demand in support joints.

In 2009, Fu et al. [133] investigated the progressive failure of a 20-story steel building under various column removal scenarios using the ABAQUS finite element software. The modelling considered geometrical and mechanical nonlinearities and was validated based on previous tests performed on subassemblies. The results showed that the models can accurately predict the overall behaviour of a 20-story building against progressive collapse and provided useful information for future structural robustness design.

Later, in 2012, Fu [134] created 3D finite element models, again using the ABAQUS software, to investigate the behaviour of steel-framed composite structures against progressive collapse caused by successive column removal scenarios. The results showed that different column removal sequences can cause plasticity in the structure, activating ALPs and resisting mechanisms. It was also found that removing the corner column causes more damage to the system.

In 2013, Song and Sezen [29] presented results of an experimental campaign which involved removing 4 columns from the existing steel-framed Ohio Union building that was scheduled for demolition. The experimental results were used to assess the suitability and effectiveness of several FEM-based methods used for progressive collapse design, namely: linear static, nonlinear static, linear dynamic, and nonlinear dynamic analyses of ALPs after column removal. The results showed that amplification factors recommended for simplified analysis in an older version of UFC 4-023-03 [135] could lead to very conservative outcomes. It is worth highlighting that these amplification factors have since been modified in the latest version of this code [5].

In 2014, Gerasimidis [136] used a previously validated analytical method [137] to study the progressive collapse of multi-storey steel frames after corner-column failure. It was shown that column buckling is one of the most important phenomena to consider in the case of failure of columns in lower floors. On the other hand, flexural failure of beams was found to be more critical after failure of columns in higher floors.

In 2016, Johnson et al. [138] conducted several experimental tests on a ½-scale steel frame-composite floor building structure under various column removal scenarios, including corner-column removal. The specimen, designed for efficient gravity load transfer in a typical commercial building, allowed the structural continuity and progressive collapse behaviour of structures of this type to be analysed. The results showed that gravity systems for commercial buildings do have a significant capability to redistribute loads, even if they have not been specifically designed for progressive collapse. However, the resisting capacity was found to be reduced by 28% in the corner-column removal scenario when compared to edge-column removal. They also found that load redistribution occurred thanks to the activation of tension ties as well as due to flexural action in the case of corner-column removal. Finally, they concluded that for this specific case the capacities obtained for the examined frames were not sufficient to prevent progressive collapse if it occurs at the accidental load combination established in applicable building codes.

Table 6. Previous progressive collapse research involving steel-framed buildings under corner column removal scenarios. The number of citations shown is up to September 2022.

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Chua et al. (2022) [139]	It was shown that dynamic amplification factors used in nonlinear static analysis overestimate the displacement response of steel modular buildings in column removal scenarios.	Yes	FEM	No	-	4
Shokoohfar & Kaafi Siyahestalkhi (2022) [140]	The presence of openings in the composite floors of steel moment-resisting frame buildings can reduce the ability of the structure to withstand loads. It was found that an opening in the middle of the building causes more axial loads around the site of a removed corner column compared to one which is closer to the corner.	Yes	FEM	No	-	-
Anusha & Nahushananda Chakravarthy (2022) [141]	For the structure being analysed, corner column removal resulted in the smallest vertical deflection while interior column removal resulted in the greatest, with the latter being the most critical case. The effect of different bracing systems was also studied, and X-bracing was found to have good progressive collapse performance.	Yes	FEM	No	-	-
Yang et al. (2022) [142]	A design procedure to avoid failure in composite steel frames is proposed in Chapter 4 based on experimental tests and computational modelling. The simulations performed included cases of corner column removal.	Yes	FEM	No	-	-
Elsanadedy et al. (2022) [125]	Several sequential and simultaneous multi-column removal scenarios are analysed, and the most critical ones are identified. Based on the analysis performed, dynamic Increase factors for linear static analyses are recommended for both force and deformation-controlled actions.	Yes	FEM	No	-	-
Alembagheri et al. (2021) [143]	It was found that the modular steel buildings investigated are sufficiently robust to avoid failure propagation after the loss of a single corner column or of a single module. However, the simulations predict the occurrence of progressive collapse for combined module removal scenarios.	Yes	FEM	No	-	1
He et al. (2021) [144]	In steel Modular integrated Construction (MiC) structures, inter-module connection types greatly influence the beam-column joint properties which dominates progressive collapse resistance. A simplified macro-modelling approach is proposed for this structural type.	Yes	FEM	No	-	8

Authors and year	**Main findings and contribution**	**Analytical or numerical modelling**		**Experimental**		**Cited by (SCOPUS)**
		Yes / No	**Method**	**Yes/No**	**Scale**	
Thai et al. (2021) [145]	Bracing systems can enhance the structural robustness of modular buildings. The removal of corner members from such structures was found to be more critical due to the presence of fewer adjacent elements for load redistribution.	Yes	FEM	No	-	3
Qiao et al. (2020) [146]	Two calculation models of progressive collapse resistance are proposed for middle and corner column removal considering the combined contributions of bending, Vierendeel and catenary action. It was also shown that bracing systems can improve structural robustness.	Yes	Analytical, FEM	No	-	8
Hu & Zhao (2020) [147]	Dynamic increase factors for most models were found to be close to 1.5. Cross braces could help mitigate effects of column failure in the affected bay, decreasing the peak displacement by more than 50% after corner column failure.	Yes	FEM	No	-	2
Zhang et al. (2020) [148]	Several multi-column-removal scenarios were investigated. It was found that linearly consecutive column losses have less adverse effects compared to the loss of multiple columns in a rectangular pattern. When the imposed loads are low, the structure proved to be most robust against corner-column-related losses whereas at higher load levels it proved most robust against interior column losses.	Yes	FEM	No	-	3
Galal et al. (2019) [149]	It was shown that 3D and 2D skeleton frames cannot accurately represent the structural response during progressive collapse. Of all the single-column removal scenarios investigated, the removal of the corner column from the ground floor of a structure with double web angle connections proved to be the most vulnerable to progressive collapse.	Yes	FEM	No	-	6
Chen et al. (2018) [150]	For hybrid structures consisting of composite steel frames with a reinforced concrete core, it was concluded that the loss of a shear wall or of a corner column were most likely to cause progressive collapse if they were to occur prior to or during an earthquake.	Yes	FEM	Yes	1/5	7
Qiao et al. (2018) [151]	Simplified models for calculating the resistance provided by beam, catenary and Vierendeel mechanisms are proposed and validated in this research.	Yes	Analytical, FEM	No	-	19
Hamidi et al. (2018) [152]	Based on the scenarios studied, corner column removal was found to be more critical than edge column removal. It was also shown that viscous dampers can improve dynamic structural response after column loss in certain cases.	Yes	FEM	No	-	-

Authors and year	**Main findings and contribution**	**Analytical or numerical modelling**		**Experimental**		**Cited by (SCOPUS)**
		Yes / No	**Method**	**Yes/No**	**Scale**	
Rahnavard et al. (2018) [153]	Based on the scenarios studied, the removal of edge columns was found to be more critical than that of corner columns. In general, it was found that fluctuations damped sooner in buildings with a regular arrangement in plan compared to those with an irregular one.	Yes	FEM	No	-	24
Kordbagh & Mohammadi (2018) [154]	It was shown that it is important to consider panel zone effects when simulating the progressive collapse of steel frames. In particular, these effects were shown to be important when simulating corner column removal in structures with I-section columns.	Yes	FEM	No	-	3
Nazri et al. (2018) [155]	Based on the cases studied, it was found that moment-resisting steel frames had a lower progressive collapse potential compared to steel frames. The study also found corner column loss to be more critical than interior column loss.	Yes	FEM	No	-	-
Pujari & Sangle (2018) [156]	Based on the structure analysed, the loss of corner columns was found to be more critical than the loss of middle edge columns.	Yes	FEM	No	-	-
Akbarinia et al. (2018) [157]	Buckling restrained braced frames were found to have better progressive collapse performance compared to conventional frames. Based on the cases studied, corner column removal was found to be more critical than interior columns.	Yes	FEM	No	-	1
Kordbagh & Mohammadi (2017) [158]	Based on the cases studied, it appears buildings with more storeys are safer against progressive collapse. In addition, structures with greater base shear resistance perform better against progressive collapse.	Yes	FEM	No	-	14
Chu et al. (2017) [159]	For the structure studied, no catenary resisting mechanism could develop in beams after the loss of a corner column although it could develop after the loss of a middle column.	Yes	FEM	No	-	2
Nanaiya et al. (2017) [160]	Removal of a corner column proved to be most critical compared to all removal scenarios analysed.	Yes	FEM	No	-	1
Bandyopadhyay & Banik (2016) [161]	From the numerical study of different 10-storey frames with semi-rigid connections, it was found that bracings significantly improve progressive collapse resistance and that placing them in a floor-wise arrangement is more effective than placing them in a bay-wise arrangement.	Yes	FEM	No	-	1

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Mashhadiali et al. (2016) [162]	Based on the numerical study of 50-storey building models, it was concluded that the steel plate shear wall lateral load-resisting system has greater progressive collapse resisting potential compared to X-braced and moment frame structures. The most vulnerable structural components in each of these systems is also identified.	Yes	FEM	No	-	12
Johnson et al. (2016) [138]	Load redistribution in the tested system was found to occur mainly due to composite flexural response and through the activation of tension ties. The load capacity after corner column removal was found to be 28% lower than that after edge column removal. All the observed capacities were lower than the extreme event load combination commonly used for progressive collapse design.	No	-	Yes	1/2	63
Hosseini et al. (2016) [163]	It was shown that buckling restrained braces can improve the progressive collapse performance of buildings. For the cases investigated, it was found that corner column removal is more critical compared to middle column removal.	Yes	FEM	No	-	1
Jeyarajan et al. (2015) [164] Jeyarajan et al. (2015) [165]	Analysis results reveal that simple braced frames are more vulnerable to progressive collapse compared to moment resisting frames. Various strengthening approaches for simple braced frames are also evaluated and compared in this study.	Yes	FEM	No	-	9, 16
Gerasimidis et al. (2015) [166]	It was shown that it is important to use three-dimensional structural models that consider material and geometric nonlinearities for progressive collapse analysis. For the structure analysed, removal of a corner column caused its two adjacent columns to fail due to flexural-torsional buckling, triggering sequential buckling of multiple columns and resulting in the collapse of the entire structure.	Yes	FEM	No	-	32
Yang & Wang (2015) [167]	Based on the analyses performed, it was found that decreasing joint rotational stiffness has a negative impact on progressive collapse performance. Of all the scenarios investigated, this effect was found to be greater when the corner column was removed.	Yes	FEM	No	-	-
Gao & Guo (2015) [168]	A modelling strategy with improved computational efficiency is validated in this study. The model of a 20-storey building is then developed and proposed as a benchmark for the standardisation of design for progressive collapse prevention.	Yes	FEM	No	-	12

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Valadbeigi & Ghassemieh (2014) [169]	Based on the cases studied, it was found that the vertical displacement after column loss is reduced in structures with more storeys. For these cases, corner column removal was found to be more critical than edge column removal.	Yes	FEM	No	-	-
Khalili-Tehrani et al. (2014) [170]	The design of secondary beams and slab reinforcement were shown to be critical for resisting collapse through the development of compressive arching and membrane action. The design of ductile shear connections was found to be key for providing resistance against collapse in steel braced frames. It was deemed that catenary action was of little significance for the cases studied.	Yes	FEM	No	-	3
Hosseini et al. (2014) [171]	Based on analysis results, it was concluded that steel moment resisting frames designed according to the Iranian national building codes do not satisfy criteria of UFC-4-023-03 for progressive collapse resistance. Some suggestions for improving the building codes are also described.	Yes	FEM	No	-	9
Gerasimidis (2014) [136]	An analytical method for the vulnerability assessment of damaged systems is applied to study the effect of several factors on the progressive collapse of steel frames after corner column loss. It was found that collapse mechanisms after column removal in lower floors is governed by column buckling, whereas the mechanisms after column removal in higher floors are governed by the flexural failure of beams.	Yes	Analytical	No	-	53
Kim & Jung (2013) [172]	The analysis revealed that tilting of structures requires increased steel tonnage due to an increased p-delta effect and that there is a wider distribution of plastic hinges in tilted building structures after edge or corner column removal. Nevertheless, it was deemed that such structures can have an equivalent resisting capacity after column loss if designed properly.	Yes	FEM	No	-	12
Spyridaki et al. (2013) [137]	A proposed analytical method was validated by comparing results from numerical simulations to those obtained by applying the method.	Yes	Analytical, FEM	No	-	3
Tavakoli & Alashti (2013) [173]	Based on the cases studied, corner column removal was found to be more critical compared to middle edge column removal. The capacity of a structure to resist progressive collapse under lateral loading was found to increase as the number of bays and storeys increase.	Yes	FEM	No	-	29

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Song & Sezen (2013) [29]	Experimental results obtained after removing 4 columns from an existing steel frame building are presented in this article. These are combined with results from computational simulations to evaluate the effectiveness of commonly used progressive collapse design methods. It was found that using a dynamic amplification factor of 2 can be very conservative.	Yes	FEM	Yes	1	119
Wang et al. (2012) [174]	For a single storey structure, it was found that removing the corner column is the most critical scenario. However, this was found to change as the number of storeys increase. A simplified approach for progressive collapse analysis involving modelling storeys at weights is also proposed in this research.	Yes	FEM	No	-	-
Parsaeifard & Alahi (2012) [175]	It was concluded that the capacity of the studied structure to resist lateral loads would reduce significantly if a corner column were to fail and that the damaged structure would no longer exhibit ductile behaviour during an earthquake.	Yes	FEM	No	-	1
Fu (2012) [134]	A finite element modelling technique developed by the author was used to evaluate the behaviour of a multi-storey steel composite building under consecutive column removal scenarios. Measures to mitigate progressive collapse are recommended based on analysis outcomes.	Yes	FEM	No	-	33
Yu et al. (2010) [176]	Several modelling approaches for progressive collapse assessment are evaluated in this study. The importance of considering slab effects was highlighted and a simplified dynamic assessment procedure is recommended for multi-storey buildings after column loss.	Yes	FEM	No	-	11
Song et al. (2010) [30]	Experimental results obtained by removing columns from two existing buildings are presented in this study. This together with results from computational simulations are used to provide practical and fundamental information on the collapse response of buildings with a regular structural arrangement.	Yes	FEM	Yes	1	11
Fu (2009) [133]	Design guidance for progressive collapse is given based on results obtained by applying a validated modelling strategy to the analysis of a 20-storey building.	Yes	FEM	No	-	190
Bae et al. (2008) [177]	Removal of corner wall columns were shown to cause progressive collapse of a portion of the cold-formed steel frame structure analysed.	Yes	FEM	No	-	25

Authors and year	Main findings and contribution	Analytical or numerical modelling		Experimental		Cited by (SCOPUS)
		Yes / No	Method	Yes/No	Scale	
Vlassis et al. (2008) [131]	A new design-oriented methodology for progressive collapse assessment of multi-storey buildings is applied to the case of a typical steel-framed composite building. It was demonstrated that tying force requirements alone cannot always guarantee structural robustness without explicit consideration of ductility demand in support joints.	Yes	FEM	No	-	220

6. Discussion

The most striking observation that can already be made on the basis of the descriptive statistics presented in Section 2 is the tremendous difference between the amount of research that has been performed on corner-column failures in precast concrete buildings compared to the amount of research performed on cast-in-place concrete and steel buildings. To a certain extent, this could be expected since the development of prefabricated construction systems is more recent compared to the other two types of structural systems. Nevertheless, precast concrete construction does have significant advantages in terms of cost-effectiveness, quality assurance, and durability, which means it can play a significant role in the necessary transformation towards more sustainable construction practices. Many stakeholders in the construction industry have recognised this potential, leading to more widespread use of precast concrete components. When it comes to structural robustness however, the fact that there is inherently less structural continuity in precast concrete systems means that providing ALPs to prevent failure propagation may be more challenging. As such, in order to ensure that buildings do not only become more sustainable, but also more resilient, it is clear that more research is required towards better understanding the response of precast concrete buildings after corner-column failure and towards developing solutions to enhance their robustness. More experimental research is considered as being particularly important since all previous works found on this issue for precast concrete buildings were based on computational simulations [25,119–122]. However, these studies have shown that the continuity provided by the joints between precast elements is crucial in determining the progressive collapse resistance of this type of structure.

For both concrete and steel framed buildings, several works demonstrate that Vierendeel action is a dominant secondary resisting mechanism which contributes significantly to improving progressive collapse resistance [10,28,35,46,123,127]. On the contrary, some works suggest that these types of structural systems have a limited ability to develop catenary resisting mechanisms through beams after corner-column failures [24,127,159,170]. Nevertheless, several authors have shown that the development of membrane actions in slabs is more significant and can play an important role in the redistribution of loads after such initial failures [24,55,170].

In fact, several studies have shown that slabs can significantly increase the ultimate strength capacity of both concrete and steel framed structures after the loss of a corner-column [34,40,54,126,176]. For concrete framed buildings, different works have reported that slabs are responsible for an increase of 55% to 63% in the ultimate strength capacity of particular structural systems [34,40,54]. Similarly, several articles focusing on concrete or steel framed structures highlight that infill or shear walls can also significantly contribute to improving collapse resistance by providing more ALPs for load redistribution after corner-column failure [31,50,83,101,102,108,110,162].

Many previous works involving the simulation of complete buildings have provided comparisons between different column-loss scenarios. In the case of steel framed structures, the majority of such studies indicate that corner-column failure is more critical than other scenarios. Specifically, 11 works reported that progressive collapse was more likely to occur after corner-column loss compared to other scenarios [129,145,173,149,152,155–157,160,163,169], while only 2 works reported that the loss of either an interior or an edge column was found as being more critical [141,153]. In the case of concrete framed structures, results from such studies were far more balanced. In particular, 4 articles reported that the structural systems studied were more vulnerable to progressive collapse after corner-column removal [79,83,95,99] and 5 articles reported that the systems studied were more vulnerable after other column-removal scenarios [73,105,106,114,116]. It is interesting to note that 2 out of the latter 5 studies found the penultimate column as being the most critical for progressive collapse resistance. All these results appear to suggest that although the loss of a corner column does leave a structural system particularly vulnerable to progressive collapse, the question of which column location is most critical for progressive collapse resistance is highly case-specific.

It is worth mentioning that several other parametric studies based on numerical simulations have also analysed different aspects of possible initial failure scenarios. A common underlying conclusion from such studies include for example that having more storeys over a failed column typically leads to greater residual capacity thanks to smaller beam rotations and lower ductility demands [71,95,105,129,158,169]. Other conclusions more specific to steel frame structures include the importance of designing sufficiently ductile joints to ensure the activation of secondary resisting mechanisms [131,170] and the fact that certain types of bracing can significantly improve collapse resistance [134,141,145–147,157,161,163–165]. It is worth noting that braces can be included as part of the original design or as part of a strengthening intervention [8]. Naturally, the available options for including bracing when retrofitting an existing structure are more limited in comparison to those available when designing a new building.

Finally, another general conclusion that can be made based on this review relates to the small number of studies focusing on retrofitting exiting structures. Although significant research and professional efforts have led to the incorporation of robustness criteria in building codes and guidelines that new building designs need to comply with, a very large portion of the current building stock in the world was designed without considering structural robustness. Despite this fact, out of more than 150 references considered for this review, only 10 dealt with retrofitting or strengthening existing structures [37,41,44,112,134,140,147,164,165,178]. In particular, 5 of these concerned RC buildings [37,41,44,112,178] and 5 concerned steel frame buildings [134,140,147,164,165], 2 of which consisted of similar studies carried out by the same authors [164,165]. In addition, the retrofitting solutions studied in these works tend to be overly invasive or complex to implement. These are important limitations for their adoption in industry which makes it clear that there is a need for more research on efficient and practical methods to retrofit and strengthen existing structures to improve their progressive collapse resistance after corner-column failures.

7. Conclusions

This paper presents an exhaustive review of research on the progressive collapse of framed structures after corner-column failures. The scope of the review has been focused on the most commonly used structural systems in industry, namely those consisting of cast-in-place concrete structures, precast concrete structures, and steel structures. Both the main findings as well as the methods employed to carry out the reviewed research works were analysed, allowing meaningful general conclusions from past research and the most important future research needs to be identified. In addition, interactive and searchable summary tables of all reviewed works have also been made available at 10.5281/zenodo.7606906 to facilitate access to the information collected for this review by other researchers, to enhance its usefulness, and to ensure transparency.

One of the most meaningful conclusions that can be derived from past research on corner-column failures is that Vierendeel action tends to contribute more often to load redistribution than catenary action in beams. Another useful observation is the fact that slabs and infill walls significantly change the response of structural systems after corner-column failures and should therefore be considered in analyses aiming to be realistic.

Finally, the areas identified as needing most research effort in the future based on this review on corner-column failures include the progressive collapse of precast concrete framed buildings and the retrofitting of existing buildings. With respect to the latter, it is worth highlighting that the few solutions that have been proposed for improving the robustness of existing buildings are usually overly invasive or complex to implement and thus present several important barriers to their adoption in industry.

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References

[1] B.R. Ellingwood, Mitigating Risk from Abnormal Loads and Progressive Collapse, J. Perform. Constr. Facil. 20 (2006) 315–323. https://doi.org/10.1061/(ASCE)0887-3828(2006)20:4(315).

[2] J.M. Adam, F. Parisi, J. Sagaseta, X. Lu, Research and practice on progressive collapse and robustness of building structures in the 21st century, Eng. Struct. 173 (2018) 122–149. https://doi.org/10.1016/j.engstruct.2018.06.082.

[3] C. Pearson, N. Delatte, Ronan Point Apartment Tower Collapse and its Effect on Building Codes, J. Perform. Constr. Facil. 19 (2005) 172–177. https://doi.org/10.1061/(ASCE)0887-3828(2005)19:2(172).

[4] J.M. Russell, J. Sagaseta, D. Cormie, A.E.K. Jones, Historical review of prescriptive design rules for robustness after the collapse of Ronan Point, Structures. 20 (2019) 365–373. https://doi.org/10.1016/j.istruc.2019.04.011.

[5] Department of Defense (DoD), UFC 4-023-03: Unified Facilities Criteria - Design of buildings to resist progressive collapse, (2016).

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

[7] U. Starossek, Progressive Collapse of Structures, Second edi, ICE Publishing, 2017. https://doi.org/10.1680/pcos.61682.

[8] F. Kiakojouri, V. De Biagi, B. Chiaia, M.R. Sheidaii, Strengthening and retrofitting techniques to mitigate progressive collapse: A critical review and future research agenda, Eng. Struct. 262 (2022) 114274. https://doi.org/10.1016/J.ENGSTRUCT.2022.114274.

[9] D.O. Dusenberry, New SEI/ASCE Disproportionate Collapse Mitigation Standard, J.

Struct. Eng. 148 (2022). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003305.

[10] J.M. Adam, M. Buitrago, E. Bertolesi, J. Sagaseta, J.J. Moragues, Dynamic performance of a real-scale reinforced concrete building test under a corner-column failure scenario, Eng. Struct. 210 (2020) 110414. https://doi.org/10.1016/j.engstruct.2020.110414.

[11] F. Kiakojouri, V. De Biagi, B. Chiaia, M.R. Sheidaii, Progressive collapse of framed building structures: Current knowledge and future prospects, Eng. Struct. 206 (2020) 110061. https://doi.org/10.1016/j.engstruct.2019.110061.

[12] K. Qian, B. Li, Experimental and Analytical Assessment on RC Interior Beam-Column Subassemblages for Progressive Collapse, J. Perform. Constr. Facil. 26 (2012) 576–589. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000284.

[13] K. Qian, B. Li, J.-X. Ma, Load-Carrying Mechanism to Resist Progressive Collapse of RC Buildings, J. Struct. Eng. 141 (2015) 04014107. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001046.

[14] M. Byfield, W. Mudalige, C. Morison, E. Stoddart, A review of progressive collapse research and regulations, Proc. Inst. Civ. Eng. - Struct. Build. 167 (2014) 447–456. https://doi.org/10.1680/stbu.12.00023.

[15] K. Qian, B. Li, Research Advances in Design of Structures to Resist Progressive Collapse, J. Perform. Constr. Facil. 29 (2015) B4014007. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000698.

[16] N.V. Federova, S.Y. Savin, Progressive collapse resistance of facilities experienced to localized structural damage - An analytical review, Build. Reconstr. 95 (2021) 76–108. https://doi.org/10.33979/2073-7416-2021-95-3-76-108.

[17] F. Parisi, J.M. Adam, J. Sagaseta, X. Lu, Review of Experimental Research on Progressive Collapse of RC Structures, in: IF CRASC’17 (IV Convegno Di Ing. Forense, VII Convegno Su CRolli, Affidabilità Strutt. Consolidamento), Milan, Italy, 2017: pp. 265–276.

[18] W.-J. Yi, F. Yi, Y. Zhou, Experimental Studies on Progressive Collapse Behavior of RC Frame Structures: Advances and Future Needs, Int. J. Concr. Struct. Mater. 15 (2021) 31. https://doi.org/10.1186/s40069-021-00469-6.

[19] K. Qian, B. Li, Effects of Masonry Infill Wall on the Performance of RC Frames to Resist Progressive Collapse, J. Struct. Eng. 143 (2017). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001860.

[20] I.M.H. Alshaikh, B.H.A. Bakar, E.A.H. Alwesabi, H.M. Akil, Experimental investigation of the progressive collapse of reinforced concrete structures: An overview, Structures. 25 (2020) 881–900. https://doi.org/10.1016/j.istruc.2020.03.018.

[21] S. El-Tawil, H. Li, S. Kunnath, Computational Simulation of Gravity-Induced Progressive Collapse of Steel-Frame Buildings: Current Trends and Future Research Needs, J. Struct. Eng. 140 (2014) 1–12. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000897.

[22] S.K. Kunnath, Y. Bao, S. El-Tawil, Advances in Computational Simulation of Gravity-Induced Disproportionate Collapse of RC Frame Buildings, J. Struct. Eng. 144 (2018) 03117003. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001938.

[23] Q. Kai, B. Li, Dynamic performance of RC beam-column substructures under the scenario of the loss of a corner column—Experimental results, Eng. Struct. 42 (2012) 154–167. https://doi.org/10.1016/j.engstruct.2012.04.016.

[24] A.T. Pham, N.S. Lim, K.H. Tan, Investigations of tensile membrane action in beam-slab systems under progressive collapse subject to different loading configurations and boundary conditions, Eng. Struct. 150 (2017) 520–536. https://doi.org/10.1016/j.engstruct.2017.07.060.

[25] N. Makoond, M. Buitrago, J. Adam, Progressive collapse assessment of precast reinforced concrete structures using the Applied Element Method (AEM), in: 6th Int. Conf. Mech. Model. Struct. Eng. (CMMoST 2021), Valladolid, 2021.

[26] Y. Zhou, S.L. Wang, N. Zhao, F.Y. Li, Experimental Research and Finite Element Analysis of Progressive Collapse Resistance of RC, Chem. Eng. Trans. 51 (2016). https://doi.org/10.3303/CET1651170.

[27] V. de Biagi, B. Chiaia, Scaling in structural complexity, Complexity. 20 (2014) 57–63. https://doi.org/10.1002/CPLX.21496.

[28] M. Sasani, S. Sagiroglu, Progressive Collapse Resistance of Hotel San Diego, J. Struct. Eng. 134 (2008) 478–488. https://doi.org/10.1061/(ASCE)0733-9445(2008)134:3(478).

[29] B.I. Song, H. Sezen, Experimental and analytical progressive collapse assessment of a steel frame building, Eng. Struct. 56 (2013) 664–672. https://doi.org/10.1016/j.engstruct.2013.05.050.

[30] B.I. Song, H. Sezen, K.A. Giriunas, Experimental and Analytical Assessment on Progressive Collapse Potential of Two Actual Steel Frame Buildings, in: Struct. Congr. 2010, American Society of Civil Engineers, Reston, VA, 2010: pp. 1171–1182. https://doi.org/10.1061/41130(369)107.

[31] M. Buitrago, E. Bertolesi, J. Sagaseta, P.A. Calderón, J.M. Adam, Robustness of RC building structures with infill masonry walls: Tests on a purpose-built structure, Eng. Struct. 226 (2021) 111384. https://doi.org/10.1016/j.engstruct.2020.111384.

[32] M. Wieczorek, Investigations Concerning the Corner Part of the Reinforced Concrete Structures in the Emergency of Removing the Corner Support, Procedia Eng. 65 (2013) 135–142. https://doi.org/10.1016/j.proeng.2013.09.023.

[33] M. Buitrago, E. Bertolesi, J. Garzón-Roca, J. Sagaseta, J.M. Adam, A Parametric Computational Study of RC Building Structures under Corner-Column Removal Situations, Appl. Sci. 10 (2020) 8911. https://doi.org/10.3390/app10248911.

[34] K. Qian, B. Li, Slab Effects on Response of Reinforced Concrete Substructures after Loss of Corner Column, ACI Struct. J. 109 (2012) 845–856. https://doi.org/10.14359/51684128.

[35] K. Qian, B. Li, Performance of Three-Dimensional Reinforced Concrete Beam-Column Substructures under Loss of a Corner Column Scenario, J. Struct. Eng. 139 (2013) 584–594. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000630.

[36] K. Qian, B. Li, Experimental Study of Drop-Panel Effects on Response of Reinforced Concrete Flat Slabs after Loss of Corner Column, ACI Struct. J. 110 (2013) 319–330.

[37] K. Qian, B. Li, Strengthening and Retrofitting of RC Flat Slabs to Mitigate Progressive Collapse by Externally Bonded CFRP Laminates, J. Compos. Constr. 17 (2013) 554–565. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000352.

[38] J.M. Russell, J.S. Owen, I. Hajirasouliha, Experimental investigation on the dynamic response of RC flat slabs after a sudden column loss, Eng. Struct. 99 (2015) 28–41. https://doi.org/10.1016/j.engstruct.2015.04.040.

[39] K. Qian, B. Li, Quantification of Slab Influences on the Dynamic Performance of RC Frames against Progressive Collapse, J. Perform. Constr. Facil. 29 (2015). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000488.

[40] N.S. Lim, K.H. Tan, C.K. Lee, Experimental studies of 3D RC substructures under exterior and corner column removal scenarios, Eng. Struct. 150 (2017) 409–427. https://doi.org/10.1016/j.engstruct.2017.07.041.

[41] P. Feng, H. Qiang, X. Ou, W. Qin, J. Yang, Progressive Collapse Resistance of GFRP-Strengthened RC Beam–Slab Subassemblages in a Corner Column–Removal Scenario, J. Compos. Constr. 23 (2019) 04018076. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000917.

[42] F. Ma, B.P. Gilbert, H. Guan, H. Xue, X. Lu, Y. Li, Experimental study on the progressive collapse behaviour of RC flat plate substructures subjected to corner column removal scenarios, Eng. Struct. 180 (2019) 728–741. https://doi.org/10.1016/j.engstruct.2018.11.043.

[43] M. Guo, H. Huang, W. Zhang, C. Xue, M. Huang, Assessment of RC Frame Capacity Subjected to a Loss of Corner Column, J. Struct. Eng. 148 (2022). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003423.

[44] W. Qin, Z. Xi, X. Liu, P. Feng, X. Ou, J. Yang, Experimental and theoretical analyses of the progressive collapse resistance of NSM strengthening RC frames after the failure of a corner column, J. Build. Eng. 47 (2022) 103805. https://doi.org/10.1016/j.jobe.2021.103805.

[45] K. Qian, X.-Y. Chen, T. Huang, Dynamic response of RC beam-slab substructures following instantaneous removal of columns, J. Build. Eng. 45 (2022) 103554. https://doi.org/10.1016/j.jobe.2021.103554.

[46] K. Qian, J.-F. Cheng, Y.-H. Weng, F. Fu, Effect of loading methods on progressive collapse behavior of RC beam-slab substructures under corner column removal scenario, J. Build. Eng. 44 (2021) 103258. https://doi.org/10.1016/j.jobe.2021.103258.

[47] J. Xu, S. Wang, K. Liu, X. Quan, F. Dong, Study on Collapse Resistance of RC Frame under the Corner Column Removal Scenario, Materials (Basel). 14 (2021) 7157.

https://doi.org/10.3390/ma14237157.

[48] S.Y. Savin, V.I. Kolchunov, P.A. Korenkov, Experimental research methodology for the deformation of RC frame under instantaneous loss of column, IOP Conf. Ser. Mater. Sci. Eng. 962 (2020) 022054. https://doi.org/10.1088/1757-899X/962/2/022054.

[49] K. Du, J. Bai, N. Teng, D. Yan, J. Sun, Experimental investigation of asymmetrical reinforced concrete spatial frame substructures against progressive collapse under different column removal scenarios, Struct. Des. Tall Spec. Build. 29 (2020). https://doi.org/10.1002/tal.1717.

[50] M. Prakash, K.S. Satyanarayanan, Experimental study on progressive collapse of reinforced concrete frames under a corner column removal scenario, Mater. Today Proc. 40 (2021) S69–S74. https://doi.org/10.1016/j.matpr.2020.03.718.

[51] B. Abdelwahed, Beam-Column Joints Reinforcement Detailing Adequacy in Case of a Corner Column Loss-Numerical Analysis, Lat. Am. J. Solids Struct. 16 (2019). https://doi.org/10.1590/1679-78255536.

[52] A.T. Pham, X.D. Pham, K.H. Tan, Slab corner effect on torsional behaviour of perimeter beams under missing column scenario, Mag. Concr. Res. 71 (2019) 611–623. https://doi.org/10.1680/jmacr.18.00011.

[53] J.-Z. Zhang, G.-Q. Li, J. Jiang, Modeling structural behavior of reinforced concrete beam–slab substructures subject to side-column loss at large deflections, Adv. Struct. Eng. 21 (2018) 1051–1071. https://doi.org/10.1177/1369433217737120.

[54] N.S. Lim, Systematic study on reinforced concrete structures under progressive collapse, Nanyang Technological University, 2017. https://doi.org/10.32657/10356/70524.

[55] N.S. Lim, K.H. Tan, C.K. Lee, Reinforced Concrete Beam-Slabs with Removed Corner Column Under Point and Uniform Distributed Load, in: High Tech Concr. Where Technol. Eng. Meet, Springer International Publishing, Cham, 2018: pp. 1750–1759. https://doi.org/10.1007/978-3-319-59471-2_201.

[56] M. Wieczorek, Theoretic-Strength Concept of a Model Describing the Destruction of the Corner Part of a Slab-Column Structure, Solid State Phenom. 240 (2015) 225–231. https://doi.org/10.4028/www.scientific.net/SSP.240.225.

[57] K. Qian, B. Li, Analytical Evaluation of the Vulnerability of RC Frames for Progressive Collapse Caused by the Loss of a Corner Column, J. Perform. Constr. Facil. 29 (2015). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000493.

[58] B. Abdelwahed, B. Belkassem, L. Pyl, J. Vantomme, BEHAVIOUR OF REINFORCED CONCRETE KNEE BEAM-COLUMN JOINT IN CASE OF GROUND CORNER COLUMN LOSS-NUMERICAL ANALYSIS, in: Proc. 5th Int. Conf. Comput. Methods Struct. Dyn. Earthq. Eng. (COMPDYN 2015), Institute of Structural Analysis and Antiseismic Research School of Civil Engineering National Technical University of Athens (NTUA) Greece, Athens, 2015: pp. 3172–3183. https://doi.org/10.7712/120115.3611.782.

[59] M. Wieczorek, Comparison Experimental Tests of Behavior of the Slab-Column

Structure after Removal of the Corner Support with Simplified Models Describing the Mechanism of Destruction, Adv. Mater. Res. 969 (2014) 78–84. https://doi.org/10.4028/www.scientific.net/AMR.969.78.

[60] P. Zhang, Z.Y. Yang, H.T. Zhou, J. Hu, Resistance Analysis of RC Frame Corner Joint Subjected to Progressive Collapse, Appl. Mech. Mater. 328 (2013) 414–420. https://doi.org/10.4028/www.scientific.net/AMM.328.414.

[61] O.A. Mohamed, Assessment of progressive collapse potential in corner floor panels of reinforced concrete buildings, Eng. Struct. 31 (2009) 749–757. https://doi.org/10.1016/j.engstruct.2008.11.020.

[62] H. Helmy, H. Salem, S. Mourad, Progressive collapse assessment of framed reinforced concrete structures according to UFC guidelines for alternative path method, Eng. Struct. 42 (2012) 127–141. https://doi.org/10.1016/j.engstruct.2012.03.058.

[63] Amercian Concrete Institute (ACI) Committee 318, Building Code Requirements for Structural Concrete (ACI 318-08) and commentary, (2007).

[64] H. Helmy, H. Salem, S. Mourad, Computer-Aided Assessment of Progressive Collapse of Reinforced Concrete Structures according to GSA Code, J. Perform. Constr. Facil. 27 (2013) 529–539. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000350.

[65] GSA, Alternate path analysis & design guidelines for progressive collapse resistance, General Services Administration, Washington, DC, 2013.

[66] Y. Xiao, Y.B. Zhao, F.W. Li, S. Kunnath, H.S. Lew, Collapse Test of a 3-Story Half-Scale RC Frame Structure, in: Struct. Congr. 2013, American Society of Civil Engineers, Reston, VA, 2013: pp. 11–19. https://doi.org/10.1061/9780784412848.002.

[67] W.-J. Yi, F.-Z. Zhang, S.K. Kunnath, Progressive Collapse Performance of RC Flat Plate Frame Structures, J. Struct. Eng. 140 (2014). https://doi.org/10.1061/(ASCE)ST.1943-541X.0000963.

[68] B. Xue, J.-L. Le, Stochastic Computational Model for Progressive Collapse of Reinforced Concrete Buildings, J. Struct. Eng. 142 (2016). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001485.

[69] T. Wang, L. Zhang, H. Zhao, Q. Chen, Progressive collapse resistance of reinforced-concrete frames with specially shaped columns under loss of a corner column, Mag. Concr. Res. 68 (2016) 435–449. https://doi.org/10.1680/jmacr.15.00108.

[70] Y. Bao, J.A. Main, S.-Y. Noh, Evaluation of Structural Robustness against Column Loss: Methodology and Application to RC Frame Buildings, J. Struct. Eng. 143 (2017). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001795.

[71] L. Shan, F. Petrone, S. Kunnath, Robustness of RC buildings to progressive collapse: Influence of building height, Eng. Struct. 183 (2019) 690–701. https://doi.org/10.1016/j.engstruct.2019.01.052.

[72] S. Nyunn, F. Wang, J. Yang, Q. Liu, I. Azim, S. Bhatta, Numerical studies on the progressive collapse resistance of multi-story RC buildings with and without exterior

masonry walls, Structures. 28 (2020) 1050–1059. https://doi.org/10.1016/j.istruc.2020.07.049.

[73] P. Kumar, S. Lavendra, T. Raghavendra, Progressive collapse resistance of reinforced concrete frame structures subjected to column removal scenario, Mater. Today Proc. 61 (2022) 264–274. https://doi.org/10.1016/j.matpr.2021.09.204.

[74] V. Rajendran, A. Gopalakrishnan, Progressive collapse: Analytical study on the behavior of reinforced concrete frame using E-tabs, Mater. Today Proc. 60 (2022) 582–587. https://doi.org/10.1016/j.matpr.2022.02.117.

[75] M. Scalvenzi, S. Gargiulo, F. Freddi, F. Parisi, Impact of seismic retrofitting on progressive collapse resistance of RC frame structures, Eng. Fail. Anal. 131 (2022) 105840. https://doi.org/10.1016/j.engfailanal.2021.105840.

[76] A. Dmitriev, V. Lalin, Comparison of Different Procedures for Progressive Collapse Analysis of RC Flat Slab Structures under Corner Column Loss Scenario, Buildings. 11 (2021) 405. https://doi.org/10.3390/buildings11090405.

[77] S. Garg, V. Agrawal, R. Nagar, Case study on strengthening methods for progressive collapse resistance of RC flat slab buildings, Structures. 29 (2021) 1709–1722. https://doi.org/10.1016/j.istruc.2020.12.049.

[78] M.A. Abdulsalam, M.T.A. Chaudhary, Progressive collapse of reinforced concrete buildings considering flexure-axial-shear interaction in plastic hinges, Cogent Eng. 8 (2021). https://doi.org/10.1080/23311916.2021.1882115.

[79] T.A. Sheikh, J.M. Banday, M.A. Hussain, Study on non-linear static behavior of 2D low-rise RCC framed structure subjected to progressive collapse, Adv. Comput. Des. 6 (2021) 257. https://doi.org/10.12989/ACD.2021.6.4.257.

[80] J. Garzón-Roca, J. Sagaseta, M. Buitrago, J.M. Adam, Dynamic Punching Assessment of Edge Columns after Sudden Corner Column Removal, ACI Struct. J. 118 (2021). https://doi.org/10.14359/51728195.

[81] A. Dmitriev, V. Lalin, A. Melnikov, Validation of Computational Procedures for the Progressive Collapse Analysis of Reinforced Concrete Structures, in: 2021: pp. 215–224. https://doi.org/10.1007/978-3-030-72404-7_22.

[82] I. Ahmed, T.A. Sheikh, P. Gajalakshmi, J. Revathy, Study on failure mechanism of multi-storeyed reinforced concrete framed structures, Adv. Comput. Des. 6 (2021) 1–13. https://doi.org/10.12989/acd.2021.6.1.1.

[83] M. Prakash, K.S. Satyanarayanan, V. Thamilarasu, Progressive Collapse Analysis of Reinforced Concrete Asymmetrical Vertical Frames, in: 2021: pp. 155–167. https://doi.org/10.1007/978-981-15-9162-4_13.

[84] T.K. Ksenofontova, Progressive Destruction of Frame Buildings Made of Monolithic Reinforced Concrete, in: 2021: pp. 73–78. https://doi.org/10.1007/978-3-030-54652-6_11.

[85] M. Wieczorek, Numerical analysis of the impact of removing a corner column in a

continuous slab-column structure in relation to the experimental model, MATEC Web Conf. 310 (2020) 00054. https://doi.org/10.1051/matecconf/202031000054.

[86] S. Karimiyan, Comparison of seismic progressive collapse distribution in low and mid rise RC buildings due to corner and edge columns removal, Earthq. Struct. 18 (2020) 649–665. https://doi.org/10.12989/eas.2020.18.5.649.

[87] S. Nyunn, J. Yang, F.L. Wang, Q.F. Liu, Nonlinear dynamic analysis on progressive collapse resistance of a multi-story reinforced concrete building with slab, in: Sustain. Build. Struct. Build. a Sustain. Tomorrow, CRC Press, 2019: pp. 121–126. https://doi.org/10.1201/9781003000716-15.

[88] T.H. Divya, R. Nikhil, Progressive Collapse Triggered by Column Loss: Detrimental Effect of Span Length and Beam Depth as Per GSA and DOD Guidelines, in: 2020: pp. 455–463. https://doi.org/10.1007/978-3-030-26365-2_42.

[89] A. Mahrous, M. Ehab, H. Salem, Progressive collapse assessment of post-tensioned reinforced concrete flat slab structures using AEM, Eng. Fail. Anal. 109 (2020) 104278. https://doi.org/10.1016/j.engfailanal.2019.104278.

[90] F. Parisi, M. Scalvenzi, Progressive collapse assessment of gravity-load designed European RC buildings under multi-column loss scenarios, Eng. Struct. 209 (2020) 110001. https://doi.org/10.1016/j.engstruct.2019.110001.

[91] P. Liu, Y. Jia, G. Wu, Y. Mao, H. Wang, Nonlinear Simulation Analysis of RC Frame Beam Slab Column Spatial Synergy against Progressive Collapse Performance under Failure of Bottom Corner Columns, IOP Conf. Ser. Earth Environ. Sci. 233 (2019) 032033. https://doi.org/10.1088/1755-1315/233/3/032033.

[92] M. Nassir, J. Yang, S. Nyunn, I. Azim, F.L. Wang, Progressive Collapse Analysis of multi-story building under the scenario of multi-column removal, E3S Web Conf. 136 (2019) 04050. https://doi.org/10.1051/e3sconf/201913604050.

[93] J. Esfandiari, M.K. Latifi, Numerical study of progressive collapse in reinforced concrete frames with FRP under column removal, Adv. Concr. Constr. 8 (2019) 165–172. https://doi.org/10.12989/acc.2019.8.3.165.

[94] B.S. Abdelwahed, Numerical analysis of progressive collapse for reinforced concrete frames, Appl. Comput. Mech. 13 (2019). https://doi.org/10.24132/acm.2019.553.

[95] E. Kuncham, V.D.K. Pasupuleti, Progressive Collapse Analysis of Two-Dimensional Reinforced Concrete Framed Structure, in: 2019: pp. 599–608. https://doi.org/10.1007/978-981-13-1966-2_54.

[96] D. Kumari, Effect of span length in progressive collapse of multi-storey rc building under corner and middle column removal scenario, Int. J. Civ. Eng. Technol. 9 (2018) 449–466.

[97] N. Prakash, M. Satyanarayanan, K.S. Thamilarasu, V. Parthasarathi, T. Sharma, Assessment of progressive collapse analysis in corner and middle column removal of reinforced concrete buildings, J. Adv. Res. Dyn. Control Syst. 10 (2018) 963–967.

[98] V. Prakash, M. Satyanarayanan, K.S. Thamilarasu, V. Parthasarathi, N. Thirumurugan, Soumya, 3D nonlinear static and dynamic assessment of progressive collapse analysis of reinforced concrete buildings, J. Adv. Res. Dyn. Control Syst. 10 (2018) 955–962.

[99] S. Gowtham, M. Prakash, N. Parthasarathi, K.S. Satyanarayanan, V. Thamilarasu, 2D-Linear static and non-linear dynamic progressive collapse analysis of reinforced concrete building, Mater. Today Proc. 5 (2018) 8775–8783. https://doi.org/10.1016/j.matpr.2017.12.305.

[100] G.M. Kravchenko, E. V. Trufanova, D.S. Kostenko, S.G. Tsurikov, Structural Concepts of High-Rise Buildings Resistant to Progressive Collapse, Mater. Sci. Forum. 931 (2018) 54–59. https://doi.org/10.4028/www.scientific.net/MSF.931.54.

[101] N. Stathas, I. Karakasis, E. Strepelias, X. Palios, M. Fardis, S. Bousias, Masonry Infilling of RC Building Against Progressive Collapse in case of Loss of Column, in: 7th Int. Conf. Adv. Exp. Struct. Eng., Pavia, 2017. https://doi.org/10.7414/7aese.T2.118.

[102] T. Besoiu, A. Popa, Infill Walls Contribution on the Progressive Collapse Resistance of a Typical Mid-rise RC Framed Building, IOP Conf. Ser. Mater. Sci. Eng. 245 (2017) 022026. https://doi.org/10.1088/1757-899X/245/2/022026.

[103] D. La Mazza, L. Giordano, P. Castaldo, D. Gino, Assessment of the efficiency of seismic design for structural robustness of RC structures, Ing. Sismica. 34 (2017) 63–77.

[104] L. Zhang, H. Zhao, T. Wang, Q. Chen, Dynamic increase factor for RC frame with specially shaped columns against progressive collapse, J. Vibroengineering. 19 (2017) 419–433. https://doi.org/10.21595/jve.2016.17371.

[105] F. Attia, H. Salem, N. Yehia, Progressive collapse assessment of medium-rise reinforced concrete flat slab structures, Struct. Concr. 18 (2017) 409–420. https://doi.org/10.1002/suco.201600051.

[106] J.S. Shah, K. Karthikeyan, B.R. Shah, Study of progressive collapse analysis of transfer girder system RCC building, Int. J. Civ. Eng. Technol. 8 (2017) 324–336.

[107] L. Zhang, H. Zhao, T. Wang, Q. Chen, Parametric Analysis on Collapse-resistance Performance of Reinforced-concrete Frame with Specially Shaped Columns Under Loss of a Corner Column, Open Constr. Build. Technol. J. 10 (2016) 466–480. https://doi.org/10.2174/1874836801610010466.

[108] M. Prakash, N.P. Sarathi, K.S. Satyanarayanan, V. Thamilarasu, Robustness Evaluation of RC Bare Frame and Infilled Frame Buildings to Progressive Collapse Under Corner and Middle Column Removal Scenario, Int. J. Chem. Sci. (2016).

[109] M.D. Chiranjeevi, J. Simon, Analysis of Reinforced Concrete 3D Frame under Blast Loading and Check for Progressive Collapse, Indian J. Sci. Technol. 9 (2016). https://doi.org/10.17485/ijst/2016/v9i30/99232.

[110] H. Helmy, H. Hadhoud, S. Mourad, Infilled masonry walls contribution in mitigating progressive collapse of multistory reinforced concrete structures according to UFC guidelines, Int. J. Adv. Struct. Eng. 7 (2015) 233–247. https://doi.org/10.1007/s40091-015-0094-5.

[111] M. Wieczorek, Influence of Amount and Arrangement of Reinforcement on the Mechanism of Destruction of the Corner Part of a Slab-Column Structure, Procedia Eng. 57 (2013) 1260–1268. https://doi.org/10.1016/j.proeng.2013.04.159.

[112] T.C. Wang, Z.P. Li, H.L. Zhao, Progressive Collapse Resistance of RC Structures with Tension Cables, Appl. Mech. Mater. 405–408 (2013) 835–840. https://doi.org/10.4028/www.scientific.net/AMM.405-408.835.

[113] A. Pachenari, A. Keramati, Z. Pachenari, Investigation of progressive collapse in intermediate RC frame structures, Struct. Des. Tall Spec. Build. 22 (2013) 116–125. https://doi.org/10.1002/tal.663.

[114] L.D. Yu, H. Li, Risk Analysis of High-Rise Reinforced Concrete Frame-Shear Wall Structure in Progressive Collapse, Adv. Mater. Res. 639–640 (2013) 957–960. https://doi.org/10.4028/www.scientific.net/AMR.639-640.957.

[115] I. Hafez, A. Khalil, S. Mourad, Alternate Path Method Analysis of RC Structures Using Applied Element Method, Int. J. Prot. Struct. 4 (2013) 45–64. https://doi.org/10.1260/2041-4196.4.1.45.

[116] O. Yagob, K. Galal, N. Naumoski, Estimating progressive collapse potential in RC shear wall buildings, in: Proceedings, Annu. Conf. - Can. Soc. Civ. Eng., 2012: pp. 2960–2973.

[117] Y.D. Sun, Y.M. Lin, The Effect on The Overall Performance of Frame Structure of Local Column Destruction, Appl. Mech. Mater. 71–78 (2011) 315–320. https://doi.org/10.4028/www.scientific.net/AMM.71-78.315.

[118] O.A. Mohamed, Strategies for mitigation of progressive collapse of corner panels in reinforced concrete buildings, in: Saf. Secur. Eng. II, WIT Press, Southampton, UK, 2007: pp. 161–169. https://doi.org/10.2495/SAFE070161.

[119] N. Makoond, M. Buitrago, J.M. Adam, Computational study on the progressive collapse of precast reinforced concrete structures, in: Curr. Perspect. New Dir. Mech. Model. Des. Struct. Syst., CRC Press, London, 2022: pp. 187–188. https://doi.org/10.1201/9781003348450-87.

[120] M. El-desoqi, M. Ehab, H. Salem, Progressive collapse assessment of precast reinforced concrete beams using applied element method, Case Stud. Constr. Mater. 13 (2020) e00456. https://doi.org/10.1016/j.cscm.2020.e00456.

[121] M. Alanani, M. Ehab, H. Salem, Progressive collapse assessment of precast prestressed reinforced concrete beams using applied element method, Case Stud. Constr. Mater. 13 (2020) e00457. https://doi.org/10.1016/j.cscm.2020.e00457.

[122] S. Ravasini, B. Belletti, E. Brunesi, R. Nascimbene, F. Parisi, Nonlinear Dynamic Response of a Precast Concrete Building to Sudden Column Removal, Appl. Sci. 11 (2021) 599. https://doi.org/10.3390/app11020599.

[123] K. Qian, X. Lan, Z. Li, F. Fu, Behavior of Steel Moment Frames Using Top-and-Seat Angle Connections under Various Column-Removal Scenarios, J. Struct. Eng. 147 (2021). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003089.

[124] Q. Fu, K.-H. Tan, Numerical study on steel-concrete composite floor systems under corner column removal scenario, Structures. 21 (2019) 33–44. https://doi.org/10.1016/j.istruc.2019.06.003.

[125] H. Elsanadedy, H. Sezen, H. Abbas, T. Almusallam, Y. Al-Salloum, Progressive collapse risk of steel framed building considering column buckling, Eng. Sci. Technol. an Int. J. (2022) 101193. https://doi.org/10.1016/j.jestch.2022.101193.

[126] H. Zhang, G. Shu, R. Pan, Failure Mechanism of Composite Frames Under the Corner Column-Removal Scenario, J. Fail. Anal. Prev. 19 (2019) 649–664. https://doi.org/10.1007/s11668-019-00644-8.

[127] G. Li, J. Zhang, J. Jiang, Multi-storey composite framed-structures due to edge-column loss, Adv. Steel Constr. 16 (2020) 20–29. https://doi.org/10.18057/IJASC.2020.16.1.3.

[128] D.-Y. Kong, Y. Yang, S. Li, B. Yang, J.Y.R. Liew, Experimental and Analytical Study on Progressive Collapse of 3D Composite Floor System under Corner Column Loss, J. Struct. Eng. 148 (2022). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003288.

[129] M. Ghassemieh, S.M.R. Mortazavi, A. Valadbeigi, The effect of out of plane perpendicular beams on the ductility demand of steel moment framed structures during progressive collapse, Civ. Eng. Infrastructures J. 54 (2021). https://doi.org/10.22059/CEIJ.2020.288767.1612.

[130] S.S. Masajedian, R.G. Driver, Progressive collapse resistance of composite steel frame structures under corner column removal, in: Struct. Stab. Res. Counc. Annu. Stab. Conf. 2016, SSRC 2016, 2016: pp. 397–407.

[131] A.G. Vlassis, B.A. Izzuddin, A.Y. Elghazouli, D.A. Nethercot, Progressive collapse of multi-storey buildings due to sudden column loss—Part II: Application, Eng. Struct. 30 (2008) 1424–1438. https://doi.org/10.1016/j.engstruct.2007.08.011.

[132] B.A. Izzuddin, A.G. Vlassis, A.Y. Elghazouli, D.A. Nethercot, Progressive collapse of multi-storey buildings due to sudden column loss — Part I: Simplified assessment framework, Eng. Struct. 30 (2008) 1308–1318. https://doi.org/10.1016/j.engstruct.2007.07.011.

[133] F. Fu, Progressive collapse analysis of high-rise building with 3-D finite element modeling method, J. Constr. Steel Res. 65 (2009) 1269–1278. https://doi.org/10.1016/j.jcsr.2009.02.001.

[134] F. Fu, Response of a multi-storey steel composite building with concentric bracing under consecutive column removal scenarios, J. Constr. Steel Res. 70 (2012) 115–126. https://doi.org/10.1016/j.jcsr.2011.10.012.

[135] Department of Defense (DoD), UFC 4-023-03: Unified Facilities Criteria - Design of buildings to resist progressive collapse, (2009).

[136] S. Gerasimidis, Analytical assessment of steel frames progressive collapse vulnerability to corner column loss, J. Constr. Steel Res. 95 (2014) 1–9. https://doi.org/10.1016/j.jcsr.2013.11.012.

[137] A. Spyridaki, S. Gerasimidis, G. Deodatis, M. Ettouney, A new analytical method on the comparison of progressive collapse mechanisms of steel frames under corner column removal, in: Safety, Reliab. Risk Life-Cycle Perform. Struct. Infrastructures, CRC Press, 2014: pp. 5059–5065. https://doi.org/10.1201/b16387-734.

[138] E.S. Johnson, J.E. Meissner, L.A. Fahnestock, Experimental Behavior of a Half-Scale Steel Concrete Composite Floor System Subjected To Column Removal Scenarios, J. Struct. Eng. 142 (2016). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001398.

[139] Y.S. Chua, S.D. Pang, J.Y.R. Liew, Z. Dai, Robustness of inter-module connections and steel modular buildings under column loss scenarios, J. Build. Eng. 47 (2022) 103888. https://doi.org/10.1016/j.jobe.2021.103888.

[140] A. Shokoohfar, P. Kaafi Siyahestalkhi, Retrofitting and Rehabilitation in Steel Moment-resisting Frame with Prestressed Concrete Slab against Progressive Collapse Potential, Int. J. Eng. 35 (2022). https://doi.org/10.5829/ije.2022.35.01A.06.

[141] T. Anusha, H.G. Nahushananda Chakravarthy, Progressive Collapse of Steel-Framed Structures, in: 2022: pp. 311–323. https://doi.org/10.1007/978-981-16-2826-9_20.

[142] B. Yang, S.-B. Kang, K.H. Tan, X.-H. Zhou, Behaviour of Building Structures Subjected to Progressive Collapse, Elsevier, 2022. https://doi.org/10.1016/C2019-0-04133-7.

[143] M. Alembagheri, P. Sharafi, Z. Tao, R. Hajirezaei, K. Kildashti, Robustness of multistory corner-supported modular steel frames against progressive collapse, Struct. Des. Tall Spec. Build. 30 (2021). https://doi.org/10.1002/tal.1896.

[144] X.-H.-C. He, T.-M. Chan, K.-F. Chung, Effect of inter-module connections on progressive collapse behaviour of MiC structures, J. Constr. Steel Res. 185 (2021) 106823. https://doi.org/10.1016/j.jcsr.2021.106823.

[145] H.-T. Thai, Q.V. Ho, W. Li, T. Ngo, Progressive collapse and robustness of modular high-rise buildings, Struct. Infrastruct. Eng. (2021) 1–13. https://doi.org/10.1080/15732479.2021.1944226.

[146] H. Qiao, C. Luo, J. Wei, Y. Chen, Progressive Collapse Analysis for Steel-Braced Frames Considering Vierendeel Action, J. Perform. Constr. Facil. 34 (2020). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001475.

[147] Y. Hu, J. Zhao, Layout of cross braces on progressive collapse analysis of a 3D 12-story steel composite frame structures, J. Eng. Res. 8 (2020) 45–58.

[148] J.-Z. Zhang, B.-H. Jiang, R. Feng, R. Chen, Robustness of steel moment frames in multi-column-removal scenarios, J. Constr. Steel Res. 175 (2020) 106325. https://doi.org/10.1016/j.jcsr.2020.106325.

[149] M.A. Galal, M. Bandyopadhyay, A.K. Banik, Vulnerability of Three-Dimensional Semirigid Composite Frame Subjected to Progressive Collapse, J. Perform. Constr. Facil. 33 (2019). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001297.

[150] X. Chen, W. Xie, Y. Xiao, Y. Chen, X. Li, Progressive Collapse Analysis of SRC Frame-RC Core Tube Hybrid Structure, Appl. Sci. 8 (2018) 2316.

https://doi.org/10.3390/app8112316.

[151] H. Qiao, Y. Yang, J. Zhang, Progressive Collapse Analysis of Multistory Moment Frames with Varying Mechanisms, J. Perform. Constr. Facil. 32 (2018). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001192.

[152] H. Hamidi, F. Farokhzadeh, M.S. Amiri, Structural investigation of height-irregular-steel braced structures against progressive collapse, J. Eng. Sci. Technol. 13 (2018) 1621–1635.

[153] R. Rahnavard, F.F.Z. Fard, A. Hosseini, M. Suleiman, Nonlinear analysis on progressive collapse of tall steel composite buildings, Case Stud. Constr. Mater. 8 (2018) 359–379. https://doi.org/10.1016/j.cscm.2018.03.001.

[154] B. Kordbagh, M. Mohammadi, Influence of Panel Zone on Progressive Collapse Resistance of Steel Structures, J. Perform. Constr. Facil. 32 (2018). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001152.

[155] F.M. Nazri, M.M. Kassem, S. Shahidan, S.S.M. Zuki, S.Z. Sooria, Assessment for the Progressive Collapse of Moment Resisting Frame Structures Using a Practiced-Oriented Method, ASM Sci. J. 11 (2018).

[156] A.B. Pujari, K.K. Sangle, Progressive collapse analysis of seismically design low rise steel frame structure, ARPN J. Eng. Appl. Sci. 13 (2018).

[157] F. Akbarinia, Y. Adinehfar, H. Davashi, D. Jalili, P. Beiranvand, M. Hosseini, Investigating the effect of column removal on progressive collapse of buildings designed by buckling restrained braced and bending frames, Eng. Solid Mech. (2018) 83–88. https://doi.org/10.5267/j.esm.2017.10.001.

[158] B. Kordbagh, M. Mohammadi, Influence of seismicity level and height of the building on progressive collapse resistance of steel frames, Struct. Des. Tall Spec. Build. 26 (2017) e1305. https://doi.org/10.1002/tal.1305.

[159] L. Chu, G. Li, D. Li, J. Zhao, Study on Progressive Collapse Behavior of SRC Column-Steel Beam Hybrid Frame Based on Pushdown Analysis, Shock Vib. 2017 (2017) 1–12. https://doi.org/10.1155/2017/3075786.

[160] R. Nanaiya, I.A. Parvez, K. Kamath, Progressive collapse analysis of steel and RCC frames using linear dynamic method, Int. J. Civ. Eng. Technol. 8 (2017) 805–812.

[161] M. Bandyopadhyay, A.K. Banik, Improvement of progressive collapse resistance potential of semi-rigid jointed steel frames through bracings, Int. J. Prot. Struct. 7 (2016) 518–546. https://doi.org/10.1177/2041419616668085.

[162] N. Mashhadiali, M. Gholhaki, A. Kheyroddin, R. Zahiri-Hashemi, Technical Note: Analytical Evaluation of the Vulnerability of Framed Tall Buildings with Steel Plate Shear Wall to Progressive Collapse, Int. J. Civ. Eng. 14 (2016) 595–608. https://doi.org/10.1007/s40999-016-0044-z.

[163] M. Hosseini, P. Beiranvand, M. R. Dadgar, M.Zarei, The Effect of Column Location and Bracing on Progressive Collapse of Steel Structures, Electron. J. Struct. Eng. 16

(2016) 63–68. https://doi.org/10.56748/ejse.16211.

[164] S. Jeyarajan, J.Y. Richard Liew, C.G. Koh, Progressive collapse mitigation approaches for steel-concrete composite buildings, Int. J. Steel Struct. 15 (2015) 175–191. https://doi.org/10.1007/s13296-015-3013-5.

[165] S. Jeyarajan, J.Y.R. Liew, C. Koh, Enhancing the Robustness of Steel-Concrete Composite Buildings under Column Loss Scenarios, Int. J. Prot. Struct. 6 (2015) 529–550. https://doi.org/10.1260/2041-4196.6.3.529.

[166] S. Gerasimidis, G. Deodatis, T. Kontoroupi, M. Ettouney, Loss-of-stability induced progressive collapse modes in 3D steel moment frames, Struct. Infrastruct. Eng. 11 (2015) 334–344. https://doi.org/10.1080/15732479.2014.885063.

[167] H. Yang, L. Wang, Progressive collapse analysis of space steel frames considering influence of joint rotational stiffness, in: Adv. Civ. Eng. Build. Mater. IV, CRC Press, 2015: pp. 385–388. https://doi.org/10.1201/b18415-87.

[168] S. Gao, L. Guo, Progressive collapse analysis of 20-storey building considering composite action of floor slab, Int. J. Steel Struct. 15 (2015) 447–458. https://doi.org/10.1007/s13296-015-6014-5.

[169] A. Valadbeigi, M. Ghassemieh, Evaluation of Progressive Collapse of Special Steel Moment Frames, Adv. Mater. Res. 831 (2013) 85–89. https://doi.org/10.4028/www.scientific.net/AMR.831.85.

[170] P. Khalili-Tehrani, A. Masroor, S. Dogruel, D. Cormie, M. Gallo, I. Almufti, Lessons Learned from the Design of Steel and RC Structures against Progressive Collapse Using Nonlinear Alternate Path Analysis, in: Struct. Congr. 2014, American Society of Civil Engineers, Reston, VA, 2014: pp. 954–965. https://doi.org/10.1061/9780784413357.085.

[171] M. Hosseini, N. Fanaie, A.M. Yousefi, Studying the Vulnerability of Steel Moment Resistant Frames Subjected to Progressive Collapse., Indian J. Sci. Technol. 7 (2013) 335–342. https://doi.org/10.17485/ijst/2014/v7i3.17.

[172] J. Kim, M.-K. Jung, Progressive collapse resisting capacity of tilted building structures, Struct. Des. Tall Spec. Build. 22 (2013) 1359–1375. https://doi.org/10.1002/tal.1010.

[173] H.R. Tavakoli, A. Rashidi Alashti, Evaluation of progressive collapse potential of multi-story moment resisting steel frame buildings under lateral loading, Sci. Iran. (2013). https://doi.org/10.1016/j.scient.2012.12.008.

[174] T.C. Wang, J. Kang, Z.P. Li, H.L. Zhao, Research on Judging Key Components for Collapse of Space Structures, Appl. Mech. Mater. 166–169 (2012) 1459–1464. https://doi.org/10.4028/www.scientific.net/AMM.166-169.1459.

[175] N. Parsaeifard, F. Nateghi Alahi, Analytical Study of Seismic Progressive Collapse in a Steel Moment Frame Building, Adv. Mater. Res. 446–449 (2012) 102–108. https://doi.org/10.4028/www.scientific.net/AMR.446-449.102.

[176] H. Yu, B.A. Izzuddin, X.-X. Zha, Progressive collapse of steel-framed buildings:

influence of modelling approach, Adv. Steel Constr. 6 (2010) 932–948. https://doi.org/10.18057/IJASC.2010.6.4.

[177] S.-W. Bae, R.A. LaBoube, A. Belarbi, A. Ayoub, Progressive collapse of cold-formed steel framed structures, Thin-Walled Struct. 46 (2008) 706–719. https://doi.org/10.1016/j.tws.2008.01.041.

[178] M. Scalvenzi, S. Gargiulo, F. Freddi, F. Parisi, Impact of seismic retrofitting on progressive collapse resistance of RC frame structures, Eng. Fail. Anal. 131 (2022) 105840. https://doi.org/10.1016/j.engfailanal.2021.105840.