

NONLINEAR DYNAMIC ANALYSIS OF REINFORCED CONCRETE STRUCTURES UNDER PROGRESSIVE COLLAPSE: COMPUTATIONAL MODELING, IMPACT LOADING MECHANISMS, AND ROBUSTNESS ENHANCEMENT STRATEGIES

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Abstract

Progressive collapse of reinforced concrete structures, triggered by localized damage from events like blast or impact, remains a critical challenge in structural engineering, as evidenced by historical failures. This systematic review critically evaluates the state-of-the-art in nonlinear dynamic analysis for such scenarios, focusing on computational modeling techniques, impact loading mechanisms, and strategies for structural robustness enhancement. We synthesized findings from a broad base of peer-reviewed research, following a rigorous and transparent methodology to ensure comprehensive coverage of the field. The analysis reveals a clear evolution from early simplified experimental studies to sophisticated computational approaches, including continuum-based finite element models, discrete applied element methods, and efficient macromodeling strategies. A key finding is that conventional assumptions of idealized column removal can significantly underestimate the structural demand; instead, realistic impact simulations demonstrate a critical downward pulling force that accelerates failure propagation and alters the transition from flexural to catenary action. Furthermore, we systematically categorized and appraised various enhancement approaches, including externally bonded fiber-reinforced polymers, internal detailing modifications, and passive bracing systems, finding their effectiveness consistently linked to improved rotational ductility and enhanced tensile load paths. The review concludes that no single modeling paradigm is universally superior; the appropriate choice depends on the trade-off between predictive accuracy and computational cost for specific research or design objectives. A major practical implication is the need for design codes to explicitly account for impact-induced dynamic forces and to promote mechanisms like catenary and tensile membrane action. Future work should focus on multi-hazard optimization, ensuring that solutions for progressive collapse do not inadvertently compromise seismic performance or economic feasibility.

1. Introduction

The progressive collapse of reinforced concrete (RC) structures, characterized by the sequential propagation of initial local failure to adjoining structural members, ultimately resulting in a disproportionate extent of damage relative to the triggering event, remains one of the most formidable challenges in modern structural

engineering [1]. This phenomenon, starkly exemplified by catastrophic failures such as the partial collapse of the Ronan Point apartment tower in 1968 and the complete destruction of the Murrah Federal Building in 1995, underscores a fundamental vulnerability in our built environment [2]. The initiating events—often explosions, vehicular impacts, or severe

fires—impart intense, short-duration loads that induce complex, nonlinear dynamic responses far beyond the scope of conventional static design assumptions [3]. Understanding the mechanisms by which such localized damage escalates into global instability is paramount for developing resilient infrastructure capable of withstanding extreme, albeit rare, hazard scenarios.

At the core of progressive collapse analysis lies the necessity to simulate nonlinear dynamic behavior with high fidelity. The transition from elastic response to significant material inelasticity, characterized by concrete crushing, steel yielding, and bond-slip, must be accurately captured [4]. Furthermore, the redistribution of gravity loads through alternative load paths, such as catenary action in beams and tensile membrane action in slabs, introduces geometric nonlinearities that are inherently dynamic [5]. Computational modeling has therefore emerged as the primary tool for this purpose, enabling researchers to explore collapse mechanisms that are often too dangerous or costly to investigate experimentally. These techniques range from detailed continuum-based finite element models (FEM) that represent concrete as a distributed cracking continuum and reinforcement as discrete elements, to more computationally efficient methodologies like the applied element method (AEM), which directly simulates element separation and fragmentation [6]. More recently, macromodeling approaches, which simplify entire structural components into nonlinear spring or fiber-hinge assemblies, have gained traction for their ability to analyze full structural systems under extreme loads with manageable computational cost [7].

Despite significant progress, several critical research gaps persist, hindering the translation of advanced analysis into practical design guidance. A primary gap is the often-simplified treatment of the triggering event itself. Numerous experimental and numerical studies approximate the initiation of collapse by suddenly removing a load-bearing column, a procedure codified in guidelines like the General Services Administration (GSA) and Department of Defense (DoD) criteria [8]. While this "alternate path" method provides a tractable benchmark, it fundamentally neglects

the dynamic, impulsive nature of the initiating load. Recent investigations have demonstrated that simulating a realistic impact event—where a car or debris strikes a column—produces a significantly more severe structural response than an instantaneous column removal [9]. The impact generates a downward pulling force on the surrounding structure, accelerating damage propagation and altering the transition from flexural to catenary action. This discrepancy suggests that current design provisions may systematically underestimate the true collapse potential. Another substantial gap involves the integrated treatment of structural robustness enhancement strategies. While numerous individual solutions—such as externally bonded fiber-reinforced polymers (FRP), seismic detailing enhancements, and the addition of steel braces—have been proposed and tested in isolation, a comprehensive understanding of their comparative effectiveness, interaction mechanisms, and potential trade-offs remains elusive [10]. Furthermore, the probabilistic nature of progressive collapse, including uncertainties in material properties, loading magnitudes, and structural geometries, is rarely incorporated systematically into design frameworks, leaving a gap between deterministic analysis and the stochastic reality of hazard events.

The motivation for this systematic review stems directly from these identified deficiencies. There exists a pressing need to synthesize the fragmented body of knowledge on nonlinear dynamic analysis, impact loading, and robustness enhancement into a coherent, actionable framework. The primary contribution of this work is to critically evaluate and integrate the diverse computational modeling paradigms—from continuum FEM to macromodels—assessing their respective strengths and limitations for simulating different aspects of progressive collapse. We aim to clarify the crucial mechanistic differences between idealized column removal and realistic impact scenarios, particularly regarding the dynamic redistribution of forces and the triggering of alternative load paths. Furthermore, we seek to systematically categorize and compare the reported effectiveness of various structural robustness enhancement

approaches, moving beyond isolated case studies to identify generalizable design principles. By doing so, this review provides a clear roadmap for future research, pinpointing areas where experimental validation is most needed and where computational tools require further refinement. This work is significant because it directly addresses the gap between advanced numerical analysis capabilities and the practical design methods that are essential for constructing safer, more resilient RC structures. The remainder of this paper is organized as follows: Section 2 details the systematic methodology employed for literature search, screening, and data extraction. Section 3 then presents the comprehensive results of our analysis, which is structured across six key themes. Subsection 3.1 provides an overview of publication trends over time, revealing the evolving focus of the field. Subsection 3.2 summarizes the characteristics of the included studies. Subsection 3.3 delves into computational modeling techniques, critically comparing continuum, discrete, and macromodels. Subsection 3.4 dissects experimental and hybrid investigations, with a focus on the dynamic mechanisms of impact versus column removal. Subsection 3.5 reviews enhancement strategies. Finally, Subsection 3.6 addresses probabilistic and risk assessment frameworks. The implications of these findings for current design codes and future research directions are then discussed in Section 4, before concluding remarks are offered in Section 5.

2. Methodology

The methodological framework for this systematic review was designed to ensure transparency, reproducibility, and comprehensiveness in synthesizing the existing literature on nonlinear dynamic analysis of reinforced concrete structures under progressive collapse. We adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [11] to structure the review process, which encompasses protocol development, literature search, screening, eligibility assessment, and data synthesis.

2.1 Review Protocol

We developed a detailed review protocol prior to initiating the literature search, specifying the research question, search strategy, inclusion and exclusion criteria, and data extraction procedures. The research question was formulated using the Population, Exposure, and Outcome (PEO) framework: the Population comprised reinforced concrete structures, the Exposure encompassed progressive collapse scenarios triggered by impact loading or sudden column loss, and the Outcome included nonlinear dynamic responses and structural robustness characteristics.

The literature search was conducted across six major databases and search engines, selected for their relevance and coverage in structural engineering, computational mechanics, and disaster resilience research. We began with **Scopus**, which offers broad interdisciplinary coverage and robust citation tracking capabilities, making it a primary resource for engineering literature. **Web of Science** was subsequently searched for its curated collection of high-impact journals and conference proceedings, providing access to rigorously peer-reviewed research. **ScienceDirect**, a repository for Elsevier's extensive engineering and scientific content, was included for its strength in publishing applied mechanics and structural engineering studies. **SpringerLink** contributed access to a wide range of engineering monographs and journal articles, particularly relevant for computational modeling research. **IEEE Xplore** was consulted for its coverage of computational methods and simulation techniques, though its primary focus on electrical engineering limited its yield. Finally, **Google Scholar** was used as a supplementary search engine to capture grey literature, conference papers, and preprints not indexed in the commercial databases.

The search strings were constructed using Boolean operators and adapted to the specific syntax of each database. The core keyword combination was: ("nonlinear dynamic analysis" OR "progressive collapse" OR "impact loading") AND ("reinforced concrete" OR "RC structures") AND ("computational modeling" OR "numerical simulation" OR "finite element") AND ("robustness" OR "structural robustness")

OR "enhancement"). For Scopus, we used the string: TITLE-ABS-KEY (("nonlinear dynamic analysis" OR "progressive collapse" OR "impact loading") AND ("reinforced concrete" OR "RC structures") AND ("computational modeling" OR "numerical simulation" OR "finite element") AND ("robustness" OR "structural robustness" OR "enhancement")). For Web of Science, we employed: TS= (("nonlinear dynamic analysis" OR "progressive collapse" OR "impact loading") AND ("reinforced concrete" OR "RC structures") AND ("computational modeling" OR "numerical simulation" OR "finite element") AND ("robustness" OR "structural robustness" OR "enhancement")). For ScienceDirect, the search was limited to title, abstract, and keywords fields with the same Boolean logic. For SpringerLink and Google Scholar, simplified strings were used due to search character limits, focusing on the core terms: "nonlinear dynamic analysis" "progressive collapse" "reinforced concrete" "computational modeling". We did not impose a publication year restriction to capture the full historical evolution of the field.

2.2 Taxonomical Dimensions of the Review

To structure the synthesis of the included studies, we organized the literature according to five thematic dimensions that reflect the core research axes of the review. The first dimension encompasses studies focused on **Computational Modeling and Simulation Techniques**, which examine the development, validation, and application of numerical methods—such as finite element analysis, applied element method, and macromodeling approaches—for simulating nonlinear dynamic collapse behavior. The second dimension covers **Experimental and Hybrid Investigations of Progressive Collapse Mechanisms**, comprising studies that combine experimental testing with numerical simulation to elucidate the physical mechanisms of damage initiation, load redistribution, and failure progression under impact or sudden column loss. The third dimension addresses **Structural Robustness Enhancement and Mitigation Strategies**, which evaluate the effectiveness of various strengthening techniques, including fiber-reinforced polymers, seismic detailing, passive bracing, and alternative load path provisions, in improving collapse resistance. The

fourth dimension includes **Probabilistic, Reliability, and Risk Assessment Frameworks**, which incorporate stochastic modeling of uncertainties in material properties, loading scenarios, and structural geometries to quantify collapse risk and inform design decisions. Finally, a fifth dimension captures studies categorized as **Others**, which address peripheral but relevant topics such as multihazard interactions, code development, or economic implications that do not fit neatly into the primary four dimensions. This taxonomical structure enables a coherent and comparative analysis across different methodological and substantive perspectives within the field.

2.3 Inclusion and Exclusion Criteria

We established clear inclusion and exclusion criteria to ensure that only studies directly relevant to the research question and meeting minimum quality standards were selected. The inclusion criteria required that studies: (a) focus on nonlinear dynamic analysis of reinforced concrete structures under progressive collapse scenarios, including computational modeling techniques such as finite element method, discrete element method, or applied element method; (b) address impact loading mechanisms, including sudden column loss, blast, or vehicle impact, as triggers for collapse; (c) investigate structural robustness enhancement approaches, such as alternate load paths, catenary action, or strengthening systems; (d) be published as peer-reviewed journal articles or peer-reviewed conference proceedings; (e) be written in English; (f) present original research, including numerical simulations, experimental-numerical comparisons, or novel modeling methodologies; and (g) have full text available for review.

Conversely, the exclusion criteria disqualified studies that: (a) exclusively addressed steel, timber, masonry, or composite structures without a primary focus on reinforced concrete; (b) were limited to static analysis with no consideration of dynamic effects; (c) dealt only with material-level modeling (e.g., concrete constitutive laws) without structural member or system-level progressive collapse analysis; (d) addressed progressive collapse due to seismic loading unless the primary focus was on non-

seismic triggers such as impact, blast, or fire; (e) were review articles, editorials, opinion pieces, or extended abstracts without sufficient methodological detail; (f) lacked sufficient data to verify the modeling methodology, such as missing validation, unrealistic boundary conditions, or incomplete description of analysis parameters; and (g) were duplicate publications, where the same study appeared in both a conference and a journal without substantial additional content.

2.4 Study Selection Process

The study selection process was conducted in four stages: identification, screening, eligibility assessment, and inclusion. In the identification stage, we executed the search strings across all six databases, yielding a total of 561 records. After removing 248 duplicate records, we retained 313 unique records for screening. No records were removed for other reasons. In the screening stage, two independent reviewers examined the titles and abstracts of these 313 records against

the inclusion and exclusion criteria, resulting in the exclusion of 128 records that clearly did not meet the eligibility requirements. The remaining 185 reports were sought for retrieval; however, full-text copies could not be obtained for 14 of these reports due to access restrictions or incomplete publication metadata.

In the eligibility assessment stage, we retrieved and thoroughly reviewed the full-text versions of 171 reports. Each report was independently assessed by two reviewers against all inclusion and exclusion criteria. Disagreements between reviewers were resolved through discussion or consultation with a third reviewer. From this assessment, 23 reports were excluded due to ineligibility, most commonly because they focused on static analysis only, lacked sufficient validation data, or addressed primarily steel structures. Consequently, 148 studies were deemed eligible and included in the final synthesis. The entire selection process is illustrated in the PRISMA flowchart shown in Figure 1.



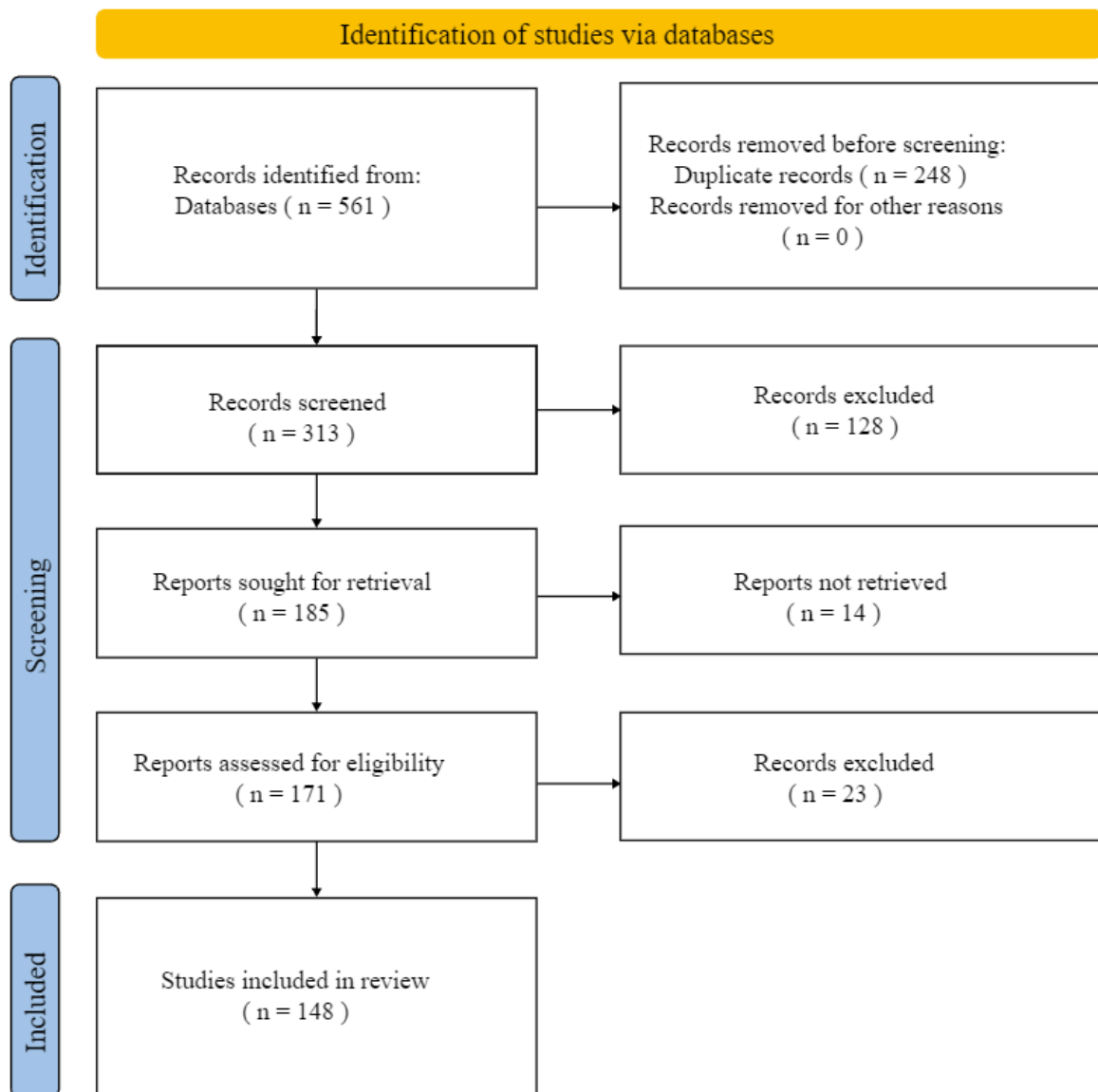


Figure 1. PRISMA flowchart illustrating the study selection process from identification to inclusion

As shown in Figure 1, the systematic and transparent selection process ensured that only high-quality, relevant studies formed the basis of this review. Nevertheless, we acknowledge several potential limitations and biases in this process. First, the restriction to English-language publications may have excluded significant research published in other languages, particularly from regions such as China or Eastern Europe where progressive collapse research is active. Second, the requirement for full-text availability may have introduced a publication bias favoring well-established journals with open access policies. Third, the

emphasis on peer-reviewed publications, while ensuring quality, may have omitted valuable contributions from industry reports or technical guidelines that lack formal peer review. Fourth, the keyword-based search strategy, although comprehensive, may have missed studies using alternative terminology, such as "disproportionate collapse" or "anti-progressive collapse design". These biases imply that our synthesis, while robust, may not capture the complete universe of relevant research, and the findings should be interpreted with this caveat in mind.

3. Results

3.1 Research Trends

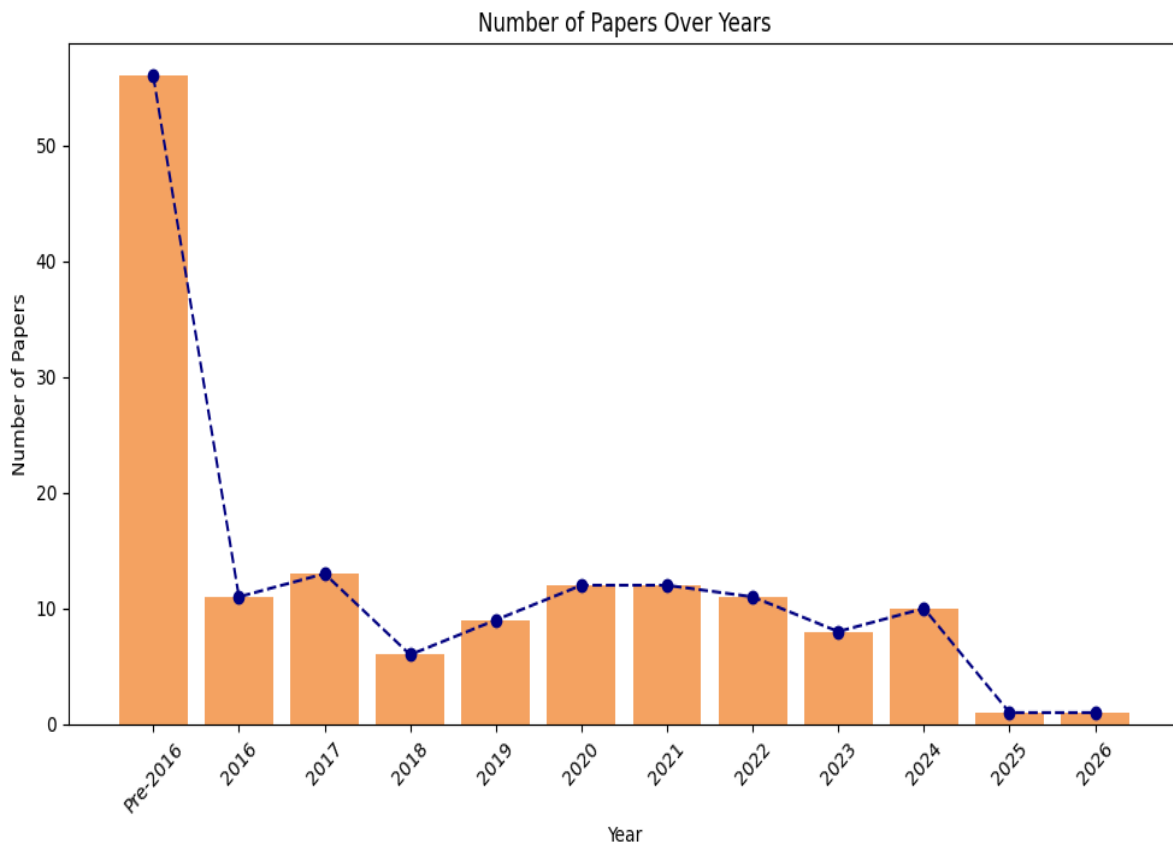


Figure 2. Research trends in the domain of Nonlinear Dynamic Analysis of Reinforced Concrete Structures Subjected to Progressive Collapse Scenarios: Computational Modeling Techniques, Impact Loading Mechanisms, and Structural Robustness Enhancement Approaches

An examination of the temporal distribution of the 148 included publications reveals a field that has exhibited sustained and substantial activity over the past decade, with a particularly pronounced growth phase emerging after 2016. Prior to this inflection point, the body of literature was already considerable, with 56 studies published before 2016, establishing a foundational knowledge base primarily focused on experimental observations and early finite element simulations of column removal scenarios. The years following 2016, however, demonstrate a clear escalation and stabilization of research output, with annual publication counts consistently ranging between 8 and 13 publications per year from 2016 through 2024, punctuated by peaks of 13 publications in both 2017 and 2021. This sustained high volume of research activity suggests that the topic has

transitioned from a marginal specialization into a mainstream research priority within structural engineering.

This temporal pattern is not merely a reflection of increasing publication pressure but likely correlates with several catalyzing factors. The maturation of high-fidelity computational platforms, such as LS-DYNA and ABAQUS, has enabled researchers to simulate impact scenarios with increasing realism, moving beyond the idealized instantaneous column removal paradigm that dominated earlier work. Furthermore, the growing awareness of infrastructure vulnerability to extreme events, reinforced by incidents of vehicular impact and deliberate attacks on critical buildings, has prompted funding agencies and research councils to prioritize progressive collapse research. Interestingly, the data for 2025 and

2026, with 1 and 1 publications respectively, should be interpreted cautiously as they likely reflect incomplete indexing at the time of the search rather than a true decline. The steady output across the last decade indicates a mature and active research community, with no evidence of a diminishing interest. Instead, the focus appears to be shifting gradually from establishing basic collapse mechanisms to more nuanced investigations concerning multi-hazard interactions, probabilistic risk quantification, and optimization of strengthening strategies, which collectively represent the evolving frontier of the field.



3.2 Overview of Included Studies

Table 1 presents the main characteristics of the included studies. The extracted information included study identification, study design, scale / specimen type, column removal scenario, structural mechanisms investigated, modeling approach and key outcomes reported, where applicable.

The included studies varied in terms of their study designs, scales of investigation, and structural mechanisms investigated, etc. These differences

provide important context for interpreting the findings of the review and for assessing potential sources of heterogeneity across the evidence base. Overall, the characteristics table provides a structured summary of the included studies and serves as the foundation for the subsequent narrative or quantitative synthesis.

Table 1. Characteristics of Included Studies

STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
[12]	Experimental test on a purpose-built full-scale reinforced concrete building with sudden column removal	Full-scale reinforced concrete building	Corner-column failure scenario via sudden removal of a specially designed corner steel column	Flexural action and Vierendeel action (alternative load paths)		Dynamic amplification of strains and displacements with high peaks; dynamic amplification factors (DAFs) were obtained; load initially carried by the removed column was redistributed through the entire building system, not just neighboring columns
[13]	Nonlinear dynamic analysis of twenty-seven different building models to evaluate impact of building height and column spacing on progressive collapse potential under UFC regulations	Dual-system reinforced concrete (RC) structures designed in the United Arab Emirates	Sudden removal of critical columns (corner, edge, and internal)	Progressive collapse, formation of plastic hinges, ductility, flexural resilience, strength of RC flat slabs	Nonlinear dynamic analysis	Corner column removal leads to more vertical displacement than edge or internal removal; adjacent columns remain elastic; RC flat slabs show insufficient flexural capacities near removed or adjacent columns

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[14]	numerical simulation / comparative study	typical reinforced concrete (RC) building / RC column		progressive collapse vulnerability	finite element modeling using LS-DYNA with CONWEP and fluid-structure interaction (ALE element formulation)	deformation response of RC column showed acceptable prediction compared to blast test results from literature
[15]	Progressive collapse analysis of a typical RC framed high-rise building exposed to blast generated waves	Typical RC framed high-rise building		Progressive collapse behavior	Practical and acceptable procedure for progressive collapse analysis	Adequacy of the procedure demonstrated by studying the progressive collapse behavior of a typical RC framed high-rise building in Riyadh when exposed to blast generated waves
[16]	Non-linear dynamic analysis	Five-story framed prestressed precast reinforced concrete structure	Corner column, edge column, and internal column near to the structure's edge	Prestressed beam behavior, prestressing cable contribution, flexure and axial loads' changes with respect to time, beam and column rotations	Applied Element Method (AEM) Extreme Loading for Structures (ELS) software	Total collapse took place in case 1; case 2 showed high capability to resist progressive collapse against all column removal scenarios; beam and column rotations calculated and compared to UFC limitations
[17]		typical multistorey reinforced concrete framed building		progressive collapse behaviour, blast vulnerability	numerical analysis	preliminary analysis has been carried out to establish vulnerability of the building when subjected to accidental or terrorist attack blast

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						scenarios; results will be used to develop mitigation approach to control or prevent progressive collapse
[18]	Progressive collapse analysis under different blast scenarios	Commercial building RC		Erosion and cratering effects	3-D finite element model using LS-DYNA with explicit time integration and solid elements with element erosion	
[19]	Experimental testing of four specimens under quasi-static loading conditions	RC beams (1 conventionally reinforced, 3 with additional mid-depth reinforcement)	Column removal scenario (specific details not provided)	Progressive collapse resistance, ductility, collapse load	Energy balance approach to convert quasi-static behavior to dynamic representation	The proposed mitigation scheme significantly improves ductility and collapse load of concrete beams subject to a column removal scenario.
[20]	experimental testing under quasi-static loading	two large-scale reinforced concrete specimens		compressive and tensile membrane actions	energy equilibrium approach proposed by Izzuddin et al. (2008) to convert non-linear response into dynamic response (Pseudo-Static response)	
[21]	Proposal and numerical validation of a new mitigation scheme for buildings	Reinforced concrete buildings	Potential column failure (sudden column loss)	Load redistribution through vertical cables transferring floor loads upward to a hat braced	Finite element modeling using ANSYS 11.0 (2008) and a simplified technique programmed	Validity of the proposed scheme for resisting progressive collapse; a

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	progressive collapse resistance			steel frame, which then redistributes loads to adjacent columns	in MATLAB 7.8.0 (2009) for designing vertical cables	simplified technique for designing vertical cables
[22]	Finite element analysis with experimental validation	Reinforced rubberized concrete frames, including full-scale frames		Progressive collapse	Finite element model using ABAQUS software	The simulation model achieved good results compared to experimental results; numerical models of full-scale frames satisfied resistance requirements of progressive collapse according to guidance.
[23]	Numerical simulation (FEM) of full-scale three-dimensional beam-slab substructures, including parametric study with eight new models	Full-scale three-dimensional (3D) beam-slab substructures		Catenary stage behavior and progressive collapse resistance	Finite element method (FEM) using ABAQUS software, with consideration of concrete and steel material non-linearity, validated using available experimental test results	Slabs contribute more than a third of load resistance and significantly improve progressive collapse resistance; rubberized concrete (RuC) specimens showed excellent performance in the catenary stage, providing additional resilience to large deformation to prevent or mitigate progressive collapse



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[24]	Numerical investigation with validation against experimental results	NC and RuC frames		Progressive collapse resistance, catenary force contribution, energy absorption, reinforcing bars fractures, concrete crushing at joint interfaces	Finite element method using ABAQUS-Explicit	CFRP composites improved progressive collapse resistance, increased ultimate load and energy absorption, prevented and delayed reinforcing bars fractures, reduced concrete crushing at joint interfaces, increased catenary force contribution
[25]	Numerical and experimental comparison	RC structures with infilled frames	Several columns on the first floor are removed	Effect of non-structural walls (infill walls) with various parameters including openings, percentage and partial infill on progressive collapse resistance	3D finite element models using ABAQUS	Reduction ratios in vertical displacement at the regions of removed columns can reach up to 80%
[26]	Three-dimensional nonlinear dynamic response analysis of reinforced concrete structures subjected to sequential column removal	Reinforced concrete frame structures (3D half-scale test used for verification)	Sequential column removal scenarios	Compressive arching action, catenary mechanism, dynamic redistribution of gravity loads	Macro modeling approach with sequential nonlinear time-history analysis	Strengthening of peripheral beams with externally bonded steel plates increases rotational ductility and enables larger deformations; sequential removal scenario yields larger permanent plastic deformations and

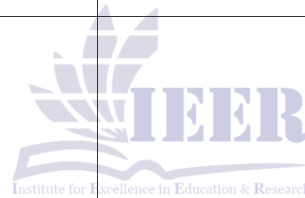
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						maximum sectional forces on average compared to at-once removal; time-lag between column removals significantly affects 3D redistribution of gravity loads and should not be neglected
[27]	Global variance-based sensitivity analysis and nonlinear incremental dynamic analysis (NIDA)	Reinforced concrete framed structures	Sudden column removal	Alternate path mechanism, axial-flexural deformation interaction, compressive arching action, progressive collapse	Plastic analysis with lumped plastic hinges, fibre-based modelling, displacement-based element (DBE) formulation, force-based element (FBE) formulation, substructure technique	Sensitivity of structural response to input uncertainties differs between lumped plastic hinge and fibre-based modelling. DBE and FBE formulations agree at low to moderate loads, but FBE is more reliable at high load factors where DBE underestimates local response and probability of failure. Substructure technique reduces computational cost in probabilistic analysis.
[28]	Post-event progressive collapse simulation of RC frame-wall structures	Multi-story RC frame-wall system	Sudden loss of a significant portion of the	Inelastic behavior, force variations in structural members, robustness of	Macromodel-based approach with simplified shear wall	No signs of collapse in either system; seismically designed frame-wall

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			shear wall at the first story	seismically designed system vs. system designed for lower seismic demands	model; detailed finite element analyses for verification	system (SDC-D) is more robust due to structural layout and seismic detailing; simplified methodology suitable for preliminary progressive collapse investigation
[28]	Numerical simulation of progressive collapse in RC moment frame structures	Two prototype RC frame buildings (designed for nonseismic and seismic regions), two-dimensional frame models	Loss of one or more first-story columns	Nonlinear behavior associated with force transfer through beam-column joints, large deformation response, progressive collapse resistance	Macromodel-based approach with simplified simulation model of beam-column joint, validated against high-fidelity finite-element analyses	Proposed macromodel approach is viable for progressive collapse analysis; special RC moment frames in high seismicity zones perform better and are less vulnerable to progressive collapse than frames designed for low to moderate seismic risk
[29]	comparative assessment of three alternative strategies for modeling column removal	reinforced concrete (RC) frame	removal of a column	progressive damage, robustness, ductility, progressive collapse	commercial nonlinear finite element software; reduction of mechanical properties of damaged column, (ii) incremental loading after total removal, (iii) incremental unloading of internal forces	similarities between structural response predictions despite different damage modeling strategies; seismic design provisions increase ductility but do not necessarily guarantee robustness to progressive collapse scenarios

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[30]	Parametric study using numerical approaches	RC framed buildings		Flexural Action, Yield Line Mechanism, Membrane Action	Finite Element Method	The slab influence is significant at the internal forces transfer and load redistribution mechanisms level: it completely changes the resisting elements behavior when considered in the numerical model.
[31]	Numerical simulation comparing three different numerical tools (OpenSees, SeismoStruct, Ls-Dyna) for progressive collapse analysis of RC buildings under blast loading leading to loss of bearing elements.	Two- and three-dimensional models of frame structures	Instantaneous removal of one or more vertical members	Progressive collapse behavior, ability of building to absorb member loss	Fiber-based force-based finite element analysis using OpenSees and SeismoStruct; transient dynamic FE analysis using Ls-Dyna; special purpose routine developed to simulate member removal	Results obtained from the three tools were compared and validated; research outcome may be applied to design, vulnerability assessment, and strengthening of residential frames to strategic and military facilities
[32]	Probabilistic fragility assessment based on pushdown analysis, Monte Carlo simulation	Low-rise reinforced concrete framed bare structures	Loss of corner column at the ground floor	Progressive collapse, dynamic amplification factor, robustness influenced by seismic design and secondary beams	Fiber-based finite element models within an open source platform, 2D and 3D structural models	Fragility functions for each damage state, comparison of pushdown analysis-derived fragility models to those from incremental dynamic analysis (IDA), regression models for dynamic amplification factor at a

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						given displacement/drift level, significant influence of seismic design and secondary beams on robustness
[33]	fragility analysis through incremental dynamic analysis, probabilistic risk assessment	low-rise reinforced concrete (RC) framed building structures	sudden removal of first-story columns	nonlinear response, resisting mechanisms, damage patterns at local and global structural levels	fiber-based finite element (FE) models, integrated with numerical techniques within an open source platform, Monte Carlo simulation	significant influence of both seismic design/detailing and secondary beams on robustness of the case-study RC building classes
[34]	Simplified theoretical model with validation against experimental data from literature	Reinforced two-span beam-column substructures	Central column subjected to a vertical load inducing progressive collapse	Flexural, arch, and catenary strength mechanisms, axial stiffness of RC compressed columns	Explicit closed-form expressions for hand calculation, step-by-step nonlinear analysis up to failure	Derived explicit expressions for push-down response and robustness evaluation of RC framed structures; design rules for robustness
[35]	Parametric study with experimental and numerical investigation	One-fifth scaled test model of a multi-column removal frame (MCRF)	Multi-column removal (implied, not explicitly detailed in abstract)	Tension membrane, compressive arch effect, and catenary effect	Numerical model established and validated according to collapse experiment	Peak impact force under increased collapse impact height (1.5–2.5 m) showed stronger local response then slightly enhanced dynamic performance; increased heaped load benefited plastic deformation capacity from catenary

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						action more than compressive arch effect; transient impact interaction almost independent of frame storey but anti-collapse performance greatly affected; collapse prediction method given to evaluate ultimate anti-collapse capacity
[36]	Experimental	RC beam-column sub-assemblages, part of five- and eight-storey moment-resisting frames	Sudden loss of a column (middle column removal simulated by monotonically increasing load at middle column)	Catenary action, progressive collapse-resisting capacity		Non-seismically designed specimen failed by concrete crushing at exterior column-girder joint before catenary action; seismically designed specimen showed increasing force-displacement after girder lower rebar fracture due to catenary action of upper rebars; significant catenary action can be induced in buildings designed per current seismic codes against progressive collapse from sudden column loss.



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[37]	nonlinear dynamic and static pushdown analysis	8-storey structure	removal of bottom-middle and bottom-corner columns	beam mechanism and catenary mechanism	PQ-Fiber model in ABAQUS program	SRC column-steel frame has good resistance to progressive collapse; after removal of bottom middle column, collapse resistance transitions from beam mechanism to catenary mechanism; after removal of bottom corner column, only beam mechanism occurs; parametric study on steel ratio, steel section size, and vertical position of removed key components
[38]	Numerical investigation using advanced finite element model validated by available test data	RC slabs with interior double-span beams	Penultimate-internal (PI) column loss	Membrane behaviour (tensile membrane action in central region, peripheral compressive ring of concrete), contribution of beam reinforcement and slab top reinforcement, slab hogging moment	Advanced finite element model (FEM)	Greater tensile membrane forces mobilised due to participation of beam reinforcement and slab top reinforcement; compressive ring strengthened by slab hogging moment; enhanced overall load-carrying capacity to sustain amplified gravity loads from double-span and dynamic effects



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[39]	Experimental and analytical study with validation against 12 beam-slab sub-assembly tests	Beam-slab sub-assemblages	Penultimate column loss	Flexural action, double span effect, dynamic effect, yield-line mechanism, displacement ductility	Simplified approach based on idealized elastic-plastic static response using yield-line method and curvature ductility of critical connection	Collapse resistance calculated from ultimate flexural capacity and displacement ductility; validated by experimental results; step-by-step procedure and design recommendations provided
[40]	Static collapse test on three asymmetric beam-column substructure specimens with flange slabs, supplemented by numerical simulation	Substructure specimens: two one-story and one two-story RC beam-column substructures with flange slabs	Penultimate column removal (OP and TP) and antepenultimate column removal (OA)	Compressive arch action (CAA), catenary action (CA), Vierendeel truss action, compression-bending failure	Fiber-beam-element-based model	Under CAA, contribution in OP and TP significantly reduced compared to OA; under CA, OA resistance developed rapidly to exceed CAA peak resistance, while OP and TP resistance varied marginally due to continuously released axial force of rebars; final failure mode was compression-bending failure of edge and penultimate columns; in OA, penultimate column damaged prior to edge column due to larger axial force; in TP,



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						Vierendeel truss action caused uneven internal force distribution leading to failure propagation from lower to upper story
[41]	Comparison of four procedures for progressive collapse analysis: linear static pull-down, nonlinear static pull-down, nonlinear dynamic, linear dynamic, and linear static pushdown and nonlinear static pushdown	RC flat slab structures	corner column loss scenario	Progressive collapse resistance under corner column loss	Detailed finite element models in ANSYS Mechanical and ANSYS/LS-DYNA, explicitly including concrete and reinforcement elements, using Continuous Surface Cap Model (MAT_CSCM) for concrete nonlinearity	Linear static pull-down and linear dynamic procedures yield 50–70% lower results than experimental; NS pull-down displacements exceed test data by 10–400%; nonlinear dynamic procedure matches test data within 7%; LS and NS pushdown methods differ from experiment by 28% and 14% respectively
[42]	Numerical simulations	Reinforced concrete bridge columns (RCBCs)		Shear mechanism, flexural response, shear response, shear failure, punching shear failure, flexural cracks, diagonal shear cracks, negative flexural-shear cracks	Numerical simulations	Impact force profile defined; new vehicle impact force model proposed; maximum dynamic shear capacity defined; failure mode classified into flexural response governed failure

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						and shear response governed failure
[43]	Nonlinear dynamic analysis and pushdown analysis on a six-story irregular reinforced concrete building, comparing four mitigation techniques.	Six-story irregular reinforced concrete building	10 independent column loss scenarios on the first floor	Progressive collapse resistance; mitigation techniques including HPFRCC, CFRP, steel plate shear wall (SPSW), and steel belt strip (SBS)	Not explicitly presented	HPFRCC reduces vertical displacement by up to 99.89%; CFRP reduces by up to 95%; SBS reduces by 97%, 89%, and 25.9% in different scenarios; maximum loading factor increased up to 2.14 times
[44]	Comparative parametric study of precast beam span lengths under different column removal scenarios using nonlinear dynamic time-dependent analysis	Full-scale precast concrete structure and bare frame structure	Column removal scenarios applied according to UFC regulations	Rotational ductility, load redistribution, resisting mechanism (slab contribution), failure cause	Applied Element Method (AEM) using Extreme Loading of Structures software	Partial collapse occurred in bare frame (Case 1); full structure with slab (Case 2) showed high resistance to progressive collapse; rotations satisfied UFC limits; no additional considerations needed for progressive collapse resistance
[45]	Numerical evaluation and proposed mitigation technique	Reinforced concrete continuous beams	Removal of interior columns	Progressive collapse, strength, ductility, effects of external unbonded FRP cables	Numerical model with rigid arms connecting external cables to beam, considering beam cross-section shape, deviator/saddle point locations, area and	Strength of mitigated beams, effects of external cables on beam ductility, comparison of numerical results to literature

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					profile of external unbonded FRP cables	
[46]	Parametric study using nonlinear finite element modeling calibrated against a scaled experimental test	Scaled, single-story, two-bay by one-bay, RC special moment resisting frame (SMRF) specimen	Middle column removal scenario	Effect of type of assembly, column continuity, development of beam rebars at exterior joints, applied axial loads on columns, and beam continuity at exterior joints on behavior under column loss; bond-slip effects at concrete-to-steel rebar interface; nonlinear rate dependent material behavior	Nonlinear finite element (FE) modeling considering rate dependent material behavior and bond-slip effects	A simple procedure proposed for progressive collapse assessment of RC SMRFs caused by sudden column removal
[47]	numerical study using finite element method	half-scale precast concrete single story two-bay frames	middle column-loss event	progressive collapse potential of precast concrete beam-to-column connections strengthened with steel plates, including material nonlinearity and strain-rate effect	nonlinear finite element models using LS-DYNA software, considering material nonlinearity for concrete, steel rebars, rubber pads, steel plates, and contact behavior between members	influence of steel plate parameters on progressive collapse behavior
[48]	Numerical study of progressive collapse in reinforced concrete frames with FRP under column removal	5-story concrete building	Removal of corner, side, and middle columns	Progressive collapse	ABAQUS software	Reinforcement of carbon fiber reinforced polymer sheets is one of the effective ways to rehabilitate and reduce

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						progressive collapse in concrete structures
[49]	Frame for quantifying structural robustness via uniform pushdown analysis	Prototype eight-story, precast/prestressed concrete moment frame system	several damage scenarios (specific scenarios not explicitly named)	Strength degradation in response to a damage event, collapse resistance	Uniform pushdown analysis within alternate path approach to progressive collapse-resistant design	Values of robustness for different damage scenarios, comparison of design alternatives based on relative robustness and consequences of potential overload
[50]	Comparative study between full-scale demolition and numerical simulation	13-story flat-slab reinforced concrete core-wall building (Pound Hall, University of Nebraska-Lincoln)	Sudden removal of columns at various locations on the ground floor; sequential blast detonation at selected column sections during demolition	Progressive collapse robustness; natural frequencies and mode shapes; displacement response	Detailed 3D nonlinear numerical model using LS-DYNA	Validated model accuracy via comparison of simulated vs. measured ambient frequencies and modes, and displacement/video from demolition; damage scenario effects on robustness of high-rise RC buildings
[51]	Non-linear static and dynamic analyses; sequential dynamic + static procedure for robustness evaluation	RC frame buildings	Sudden loss of one or more vertical load carrying member/s; critical sequence of column removals	Redistribution of axial forces following column removal; residual strength after damage	Non-linear static and dynamic analysis	Two robustness indices developed; procedure applied to two buildings to compare resistance to progressive collapse
[52]	Numerical investigation	Precast RC frame subassemblages			Efficient numerical model	

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[53]	Progressive collapse performance analysis of precast RC structures through static pushdown analysis and dynamic column-removal analysis	10-storey prototype precast RC structures	Column-removal analysis (dynamic)	Progressive collapse resisting mechanism	Numerical simulation framework in OpenSEES using fiber frame elements for beams and columns, Joint2D element for beam-to-column connections, conjugated material models with min-max failure criterion, consistent quasi-Newton algorithm for static analysis, explicit KR- α algorithm for dynamic analysis	Influences of typical parameters in precast RC structures on their progressive collapse performance
[54]	Numerical investigation of modeling strategies for progressive collapse analysis	RC frame structures				
[55]	Reliability-based approach to quantify structural robustness of RC structures subjected to progressive collapse using the probability density evolution method (PDEM).	Reinforced concrete (RC) frames	Removal of columns in typical pushdown method (initial local damage scenarios)	Progressive collapse behavior and structural reliability	Finite element model using force-based frame element; probability density evolution method (PDEM) incorporated with equivalent extreme value event	Reliability and robustness indices of frames under different initial local damage scenarios; influence of the position of initial damage scenarios on robustness
[56]	Numerical model development and	Beam-column sub-assemblages	Middle column removal	Rebar slip, rebar fracture, bond-slip behavior at	Developed in OpenSees using fiber beam-column	Satisfactory simulation of vertical load-

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	validation, then parametric study			beam-column joint, effective prestress, tendon-concrete bond behavior, tendon profile	elements for frame members, corotational truss elements for prestressing tendons, zero-length elements for bond-slip at beam-column joint, and kinematic compatibility conditions for coupling between reinforced concrete beam and prestressing tendons	displacement pushdown curves, horizontal reaction-displacement curves, and local behaviors such as rebar slip and fracture; influence of effective prestress, tendon-concrete bond behavior, and tendon profile on progressive collapse performance
[57]	Incremental dynamic analysis on both 2D and 3D structural models	Reinforced concrete frame structures with floor slabs and infill walls		3D effects, influence of floor slabs and infill walls on progressive collapse resistance, coupling effect in the space frame	Efficient numerical modeling approach developed using OpenSees software, validated by simulating different experimental test results	Secondary and/or non-structural components such as floor slabs and infill walls produce a significant improvement in the capacity of the structure to resist progressive collapse, and their respective characteristics are magnified due to the coupling effect in the space frame
[58]	Progressive collapse analysis and retrofit of a steel-reinforced concrete hospital building using	Real-scale building	Different column removal scenarios	Catenary effect, dynamic amplification factor (DIF), tensile axial resistance of beam-to-		The building is vulnerable due to low tensile axial resistance of beam-to-column

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	nonlinear static and dynamic analyses, and a two-step pushdown analysis procedure			column connections and column-to-column connections		connections; DIF = 2 and inverse relationship between DIF and deflection are ineffective due to catenary effect; retrofitted structure reduces displacement from about 20 cm to less than 1 cm; tensile strength of top three floor column-to-column connections needs increase from 565 kN to 965 kN
[59]	Progressive collapse analysis using finite element modeling	20 storey buildings	Sudden loss of columns for different scenarios of column removal	Structural behavior under sudden loss of columns for different structural systems	3-D finite element modeling method using ABAQUS with shell elements and beam elements incorporating non-linear material characteristics and non-linear geometric behavior	Models accurately displayed overall behavior under sudden loss of columns, providing important information for additional design guidance on progressive collapse
[60]	Experimental study with drop hammer impact test	Reinforced concrete beams		Effect of amount of longitudinal steel reinforcement, overall flexural failure, loading rate effects	Two-degree-of-freedom mass-spring-damper system model	Maximum midspan deflection, maximum impact load, analytical results in good agreement with experimental results

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						for beams exhibiting flexural failure
[60]		prototype RC frame		progressive collapse, initial local failure, structural reliability	3-D macro-based numerical modeling, probability density evolution method (PDEM)	The overall reliability of the structure increases as the input energy decreases. When the input energy is greater than or equal to 132 kJ, the overall reliability of the structure investigated is 0.933 for the ultimate damage criterion.
[61]	Comparative analysis of linear static and non-linear dynamic progressive collapse	2D, two bay - Five storey Reinforced Concrete (RC) bare frame	corner and middle column removal scenario	progressive collapse potential, Demand Capacity Ratio (DCR), member acceptance criteria, time vs displacement, maximum axial force, bending moment	finite element software, linear static analysis and non-linear dynamic analysis using time history method	DCR values, member acceptance criteria, Time vs Displacement, Maximum Axial force, Bending moment results where the column is removed
[62]	Comparison of Finite Element Method (FEM) and Applied Element Method (AEM) simulations to experimental results for progressive collapse analysis at three scales (small-scale connections,	Small-scale connections, mid-size building elements, and full-scale buildings (including the Pyne Gould Corporation Building in Christchurch, New Zealand).		Progressive collapse.	Finite Element Method (FEM) and Applied Element Method (AEM).	FEM predicts structural response well for small-scale models but fails to achieve realistic collapsed shapes for large structures; AEM shows convincing results in all cases.

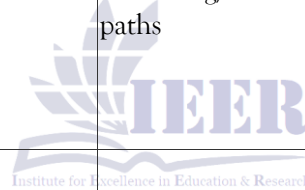
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	mid-size building elements, and full buildings).					
[63]	Experimental investigation and numerical simulation	1/4-scaled reinforced concrete substructural specimens including two beam-column subassemblies with different kinds of joints and three T-beam-column subassemblies with different beam flange widths	middle-column-removal scenario	compressive arch action (CAA) and catenary action	simplified model for nonlinear static load-deflection responses of RC two-span beams	Beam flange enhances resistance; splice length of bottom bars in beams at middle joint required by Chinese code; axial restraint of beam has significant positive effect on progressive collapse resistance but capacity unchanged when ratio of axial restraint stiffness to axial stiffness exceeds 10; progressive collapse resistance decreases with increase of span-to-height ratio
[64]	Comparison of AEM modeling with experimental tests; case study of a typical seven-story RC frame commercial building	Seven-story reinforced concrete frame commercial building		Progressive collapse; contribution of infill walls in resisting progressive collapse	Applied Element Method (AEM)	AEM is efficient in modeling progressive collapse; alternate path method can be used to optimize design even where tie force method is permitted; infill walls contribute to resisting progressive collapse

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[65]	Non-iterative progressive collapse design method based on virtual thermal pushdown analysis	Reinforced concrete (RC) structures (beam-column sub-assemblages and a full building - Alfred P. Murrah Federal Building)	Column removal scenarios (specific type not further detailed)	Progressive collapse resistance, reinforcement adequacy under column removal	Virtual thermal pushdown analysis with strength-temperature relationships for rebars	The method can directly determine the appropriate amount of reinforcement to meet performance targets, demonstrated on three examples
[66]	Fully nonlinear dynamic analysis for progressive collapse assessment according to UFC guidelines	Typical 10-story reinforced concrete framed structure designed according to ACI 318-08	Corner column, edge column, edge shear wall, internal columns, and internal shear wall	Structural integrity after support removal; effect of slabs on structural integrity	Applied Element Method (AEM)	Reinforced concrete structures designed according to ACI code do not meet UFC limits and have high potential for progressive collapse for loss of corner column or edge shear wall; a modification for the ACI code was proposed to meet UFC limits; slabs should be taken into consideration for economic design; simplification into 3D bare frames leads to uneconomic design
[67]	Static test combined with finite element analysis	Single-story 1/3 scale RC frame comprising two spans and two bays	Side column removal	Catenary action and tensile membrane action	Finite element analysis	Damage occurs only in the bay where the removal side column is located; greater catenary action and tensile

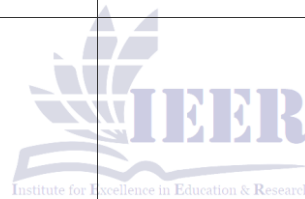
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						membrane action are mobilized at large deformations mainly in the direction of lateral restraint; simplified calculation method for catenary action and tensile membrane action proposed
[68]	Experimental study with two specimens (control and strengthened) and comparative analysis	Two 1-bay-by-2-bay two-story reinforced concrete (RC) frames	Loss of one edge column	Progressive collapse resistance, crack development patterns, load-displacement relations, lateral deformation, load distribution, effect of strengthening, contribution of slab versus beams to vertical load bearing, axial compression redistribution	Finite-element (FE) simulation and theoretical analysis	Initial stiffness and bearing capacity increased after strengthening; increasing steel strand quantity significantly increases peak load; higher floor stiffness bears more vertical load; axial compression increased on adjacent columns and decreased on diagonal columns; slab contributes less than beams, sharing about 2/3 of beam vertical load for control specimens and less than 1/2 for strengthened specimens

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[69]	Experimental test and numerical analysis of a 1-bay-by-2-bay two-story reinforced concrete frame with loss of an edge column	1-bay-by-2-bay two-story reinforced concrete (RC) frame	Loss of an edge column	Progressive collapse resistance, spatial effects, effect of slab, contributions of beams and slabs to load resistance	ABAQUS software (numerical simulation), modified dynamic resistance model (theoretical analysis)	Slabs and beams contributed approximately 1/3 and 2/3 of the load resistance, respectively; collapse phenomena, load-displacement curves, lateral displacements, and axial load distributions were recorded
[70]	Parametric analysis investigating the influence of design and material parameters on progressive collapse	Multi-storey planar frame	Sudden column loss (in the impulsive loading range)	Progressive failure patterns, effect of reinforcement ratio, ultimate strain in steel and concrete, material strain rate effects, column removal time	One-dimensional nonlinear constitutive laws for concrete and steel, layered beam approach, physically motivated relationships between generalised stresses and strains at sectional level	Significant differences observed in progressive failure patterns for the considered parametric variations
[71]	nonlinear dynamic analysis	ten-storey regular structural building	Nine independent failure scenarios: six external removal cases in different floors and three removal cases in the first floor	alternate load path to redistribute residual loads, transfer of residual loads upwards above failed column by vertical cables to a hat steel braced frame	SAP2000 software, following UFC4-023-03 document, structural design based on ACI 318-08 for special RC frames	progressive collapse of building resulting from potential failure of columns located in floors can be efficiently resisted by using this method

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[72]	Analytical model development and validation through correlation studies of RC members and a simple frame, followed by collapse analyses of multi-bay and multi-story RC frames.	RC frame structures, including multi-bay and multi-story RC frames		Bending behavior (moment-curvature relation), bond-slip effects, axial force effects, catenary action, direct shear failure (shear stress-slip relation), hysteretic unloading/reloading paths	Improved analytical model using nonlinear moment-curvature relation modified for bond-slip, axial force, and catenary action; hysteretic rules based on reinforcing steel; empirical direct shear stress-slip relation implemented via non-dimensional spring element; beam elements used to model entire frame structures	Demonstrated possibility for progressive collapse analysis of entire frame structures using only beam elements, with reduced solution steps while maintaining reliability and accuracy.
[73]	Dynamic progressive collapse analysis of planar frame structures		Failure of one or more elements	Dynamic load redistribution following element failure, interaction of axial force and bending moment, strength and stiffness degradation	Beam element formulation using multi-linear lumped plasticity model, damage-dependent constitutive relationship, damage index for member failure onset, modified member stiffness procedure without additional degrees-of-freedom or connectivity changes	Dynamic redistribution of loads is significant and should be accounted for to avoid non-conservative capacity estimates



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[74]	Experimental investigation of dynamic load redistribution performance of RC beam-column substructures following predefined initial damage caused by sudden removal of corner support.	One-third scale reinforced concrete (RC) beam-column substructures	Sudden removal of the corner support (corner column)	Dynamic load redistribution performance, progressive collapse resistance		The column removal apparatus was effective; design span length significantly affected the capability of the frames to resist progressive collapse; seismically detailed specimens mounted a more robust performance in resisting progressive collapse.
[75]	Parametric study	Reinforced concrete wall-frame structures	Middle column removal from the first story	Progressive collapse resistance considering soil-structure interaction	Simultaneous modeling of wall-frame structures along with soil (hard soil) and foundation in FLAC software, compared with frames in Seismostruct software	Sensitivity index decreased by considering soil-structure interaction; increasing foundation thickness increased sensitivity index; high groundwater levels reduce bearing capacity and lead to damage; changing substructure soil type from type 4 (Clay-MC) to type 1 (Rock), using layer 1 (SM) and layer 2 (SM-CL/ML (Very hard clay)-SM), and soils with high density improve resistance to progressive collapse



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[76]	Parametric investigation and case study analysis	Reinforced concrete tall building (Murrah Federal Building)		Progressive collapse, separation strain	Applied element method	Proposed appropriate separation strain value for progressive collapse analysis; developed two modifications to structural design and compared their expected responses to the actual building's response to bombing
[77]	Numerical simulation with gradual increase in column removal time from near zero to asymptotically approaching static response	Reinforced concrete frame structure	Three column removal scenarios due to asymmetry of the analyzed frame building	Influence of column removal rate on maximum displacement; structural vibrations and progressive collapse; comparison to static column removal	Linear and nonlinear inelastic modeling using OpenSees finite element framework; novel simplified single degree of freedom system with support removal	Impact of column removal rate depends on ability of remaining structure to withstand column loss and natural period of the downward mode shape; ratios of removal durations to natural periods identified; response spectrum for simplified model developed
[78]	numerical study based on sequential thermal-mechanical coupling method	RC frame assembly	removed column	compressive arch action (CAA), catenary action (CA), failure mode, load-resistant capacity, evolution of load-resistant mechanisms	sequential thermal-mechanical coupling method	Fire duration effects on ultimate load (decrease of 41%, 72%, 77%, 78% for 30, 60, 90, 120 min); failure controlled by beam rebar fracture near removed column for

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						short fire duration (30 min) and by rebar fracture at cut-off point for longer durations (60+ min); span-depth ratio affects deformation capacity and CAA development; reinforcement ratio effects become mild with longer fire exposure
[79]	Experimental and analytical study with monotonic lateral load up to failure	Two-story reinforced concrete frame		Progressive collapse, development and sequence of plastic hinges	Finite element analysis using OpenSees	Load-deformation curve from FEA matched well with experimental results; sequence and locations of plastic hinges from FEA corresponded with experiment; SA-based approach validated to detect locations and occurrence of plastic hinges leading to progressive collapse
[80]	Probabilistic analysis using two-scale numerical model	Two-dimensional 30 story RC structural frame	Different column removal scenarios	Progressive collapse, mixed-mode failure	Two-scale numerical model with coarse-scale cohesive elements calibrated from fine-scale stochastic finite element simulations	Occurrence probabilities of various possible collapse extents

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[81]	Experimental and computational study of reinforced concrete beam-column assemblies under a column removal scenario; two assemblies from different seismic design categories (SDC C and SDC D) were tested.	Full-scale reinforced concrete beam-column assemblies, each comprising three columns and two beams, taken from exterior moment-resisting frames of ten-story buildings.	Simulated by monotonically increasing vertical displacement of the center column.	Crushing of concrete at top of beam near center column, development of major flexural cracks (deepening and widening), fracture of bottom longitudinal beam reinforcing bars near center column.	Computational study (specific modeling approach not detailed in the provided text).	Failure was characterized by (1) crushing of concrete at the top of the beam near the center column, (2) development of major flexural cracks, and (3) fracture of the bottom longitudinal beam reinforcing bars at a major crack opening near the center column.
[82]	Numerical study comparing a new substructure technique with direct finite element modeling	Two 6-story RC frame buildings		Structural progressive collapse	Substructure technique with static condensation incorporated into the FE model	The proposed method is efficient and reliable in simulating structural response and progressive collapse with substantially less computational effort compared to direct FE model simulations
[83]	Experimental and numerical study	One-third scaled, four-bay by two-story RC frame with full-height infill walls at the second story		Influence of infill walls on progressive collapse performance, including equivalent compressive strut behavior, resistance force, initial stiffness, beam ductility, and failure mode	Finite element (FE) model for verification of test results and material parametric analyses	Maximum resistance force and failure mode are relevant to major crack developments in infill walls; infill walls improve resistance force and initial stiffness but reduce beam ductility

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						and change failure mode of RC frames
[84]	Parametric simulation and comparative analysis	Six-story reinforced concrete frame structure	Column removal and direct blast loading	Shear failure of beams/columns, failure of joints, resistance contribution from floor slab, catenary action capacity, compressive arch action capacity	Enhanced fiber beam element for beams/columns, macrojoint model for joint regions, layered shell element for slabs	The proposed model yields accurate simulation results with least cost of time. Increasing longitudinal reinforcement ratio in beams and columns increases catenary action capacity but hardly increases compressive arch action capacity. Steel mesh reinforcement at top layer of slabs plays a significant role in resisting progressive collapse.
[85]	The study develops a hybrid FEM-physics engine framework to simulate the full progressive collapse process of RC structures, including post-collapse debris accumulation.	RC frame structure; flat plate structure (for verification)	Single column removal; simultaneous removal of corner and neighboring penultimate column	Nonlinear structural behavior at small deformation, high-fidelity collapse at large deformation, debris accumulation and distribution, propagated collapse mode	Hybrid numerical framework combining finite element method (FEM) using LS-DYNA and physics engine (PE) using Blender 3D, with element merging technique and connection constraints; Python-based interface program	FEM-PE simulation achieves accurate nonlinear behavior at small deformation and high-fidelity collapse at large deformation; for reasonable debris accumulation, element numbers should be limited (beam ≤ 3 , column ≤ 2 , slab $\leq 3 \times 3$);

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						single column removal does not initiate collapse in a seismically designed RC frame, but simultaneous removal of a corner and penultimate column generates propagated collapse.
[86]	comparative design study	six-story reinforced concrete (RC) frames		strong-beam-weak-column failure mode under earthquakes	fragility curves	Progressive collapse design may cause an undesirable strong-beam-weak-column failure mode under earthquakes, necessitating seismic redesign; sequential design codes may lead to material waste and suboptimal performance; a comprehensive integrated multihazard design method is needed.
[87]	Uncertainty analysis combining fragility analysis and sensitivity analysis at component and structural levels	3-story, 4 × 3 span reinforced concrete (RC) frame structure; RC beam-column substructures (component level)	Dynamic column removal scenarios	Progressive collapse resistance, progressive collapse vulnerability, robustness, reliability	Energy-based simplified analysis method (component level); fragility curve cluster (structural level)	Failure probability of RC frame may increase by more than 30% after considering uncertainty factors; load effects, strength of reinforcement steel, and reinforcement area in beam significantly

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						affect progressive collapse resistance; a safety index proposed for judging need for progressive collapse redesign
[88]	optimization framework combining nonlinear dynamic progressive collapse design with cluster computing and global optimization algorithm	four-story RC frame structure		structural response and material consumption for progressive collapse resistance	nonlinear dynamic analysis with high-performance computing	precise control of structural progressive collapse response with optimized material consumption; comparison of global and sequential design schemes for best strategy
[89]	Numerical predictions of sub-progressive collapse in RC beam-column sub-assemblages using multiscale modeling	Beam-column sub-assemblages; 150 mm × 150 mm × 150 mm mesoscale heterogeneous model	Alternate load path method	Catenary action (CA), progressive collapse resistance, concrete failure mechanisms, fracture initiation and propagation	Finite element (FE) macromodel; 3D voxel and Voronoi-based methods for mesoscale model; concrete damage plasticity model and cohesive elements for mortar and ITZ	Good agreement of overall deformation and load resistance trends with experiments; overestimation of load resistance peak when concrete is crushed; sub-modeling provides in-depth understanding of localized cracks and fractures; aggregates and ITZ are more prone to concrete failure mechanisms under CA; mesoscale modeling facilitates comprehension



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						of fracture initiation and propagation
[90]				structural progressive collapse, nonlinear deformation before collapse, breaking and crashing of fragments after collapse, impacting and heaping of fragments	coupled finite element-discrete element method, fiber model, multi-shell model, failed finite elements removed and replaced with granular discrete elements according to criteria of equivalent total mass and volume	the coupled method not only possesses the advantages of finite element method but also simulates the behavior of fragments well
[91]	Deterministic and reliability-based robustness assessment using pushdown analysis methods	Code-conforming reinforced concrete frame structure	Simulated column loss	Reserve load carrying capacity of damaged structure, robustness for resisting progressive collapse, identification of critical key element for removal	Pushdown analysis (deterministic and reliability-based with stochastic system properties)	Quantitative assessment of robustness for resisting progressive collapse and identification of key element critical to structural global performance
[92]	Progressive collapse analysis of a typical super-tall reinforced concrete frame-core tube building under extreme fires	Super-tall reinforced concrete frame-core tube building	Flexural failure of peripheral columns triggered by fire exposure	Outward thermal expansion of upper floors and inward contraction of lower floors, Vierendeel truss mechanism for internal force redistribution	High-performance finite element model using fiber beam and multi-layer shell elements with material constitutive laws and elemental failure criteria under high temperature conditions	Progressive collapse triggered approximately 7 hours after fire exposure; bending deformations of peripheral columns increased due to thermal effects; axial forces in columns increased by approximately 100% via

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						Vierendeel truss mechanism
[93]	Experimental investigation of RC beam-slab substructures against progressive collapse subject to an edge-column-removal scenario	1/3-scaled RC frame substructure specimens, including four beam-slab specimens and one beam specimen without a slab	edge-column-removal scenario	beam mechanism (small deformations) and catenary mechanism (large deformations)		RC slabs contribute to increased collapse resistance by 146% under small deformations and 98% under large deformations compared to beam specimen; resistances mainly provided by slabs and beams along free edge; increasing seismic reinforcement in beams improves collapse resistance under both mechanisms; increasing slab thickness marginally improves resistance under catenary mechanism but not under beam mechanism; increasing beam height improves resistance under beam mechanism but not under catenary mechanism

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[94]	parametric study investigating behavior of reinforced-concrete and steel moment-frame buildings under alternate path analysis for progressive collapse	buildings (reinforced-concrete and steel moment-frame)		dynamic and nonlinear effects in progressive collapse, specifically dynamic and nonlinear load increase factors		existing guidelines tend to yield overly conservative results; new load increase factors and a new approach for utilizing these factors in alternative path analyses are proposed
[95]	Comparison of different progressive collapse simulation techniques, including quasi-static procedures and a more complete approach	Large-scale example	Not explicitly presented	Progressive collapse, load redistribution, failure of structural elements	Finite-element large displacement code with plastic hinges and beam finite elements	Discrepancies appear between results from literature procedures and reference solutions; better procedures are singled out
[96]	Analytical formulation and numerical validation	Reinforced concrete 3-bay, 3-story frame	Element removal based on dynamic equilibrium and mode-dependent gravity load collapse criteria	Progressive collapse, mode-dependent gravity load collapse of seismically deficient and retrofitted RC columns	Analytical element removal algorithm implemented into an open-source finite element code	Comparison between computationally predicted and experimentally observed collapse modes, confidence in the developed analytical formulation
[97]	Numerical investigation with pushdown simulations	Two-bay perimeter frame mock-up	Not explicitly specified (implied progressive collapse scenario)	Gravity load capacity, load eccentricity, boundary conditions, strain indicators for performance-based robustness assessment	Fibre-based modelling with different combinations of stress-strain relationships for concrete and reinforcing steel	Experimental-to-numerical load capacity ratio and overall statistical parameters; influence of capacity model properties such as material strengths, beam

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						span length, and span length ratio of asymmetric frames
[98]	Comparative study of bare and infill-wall RC frames using linear static, nonlinear static, and nonlinear dynamic analyses following GSA guidelines	Multi-story reinforced concrete (RC) buildings with and without exterior masonry walls	Column failure at corner and exterior locations	Progressive collapse resistance, load redistribution, alternate load paths, dynamic amplification factor (DAF)	Infill-wall panels simulated using equivalent compression struts	Infill walls beneficial in load redistribution and increase collapse resistance; DAF of 2 recommended by GSA guidelines is conservative; presence of infill walls does not significantly affect DAF value
[99]	Dynamic test of a RC frame under column removal	One-quarter scale, 2-bay, 2-story RC frame	Sudden loss of center column support	Compressive arch, flexural response, catenary action, snap-through effect	Single degree of freedom (SDOF) analysis	Catenary action range of response occurred at 42% of design load; snap-through effect identified as a fine tipping point between compressive arch/flexural response and catenary action; dynamic effects significantly increase loads at this point
[100]	Comparative analysis of square and rectangular concrete building plans under progressive collapse using 3D modeling and the		Removal of a corner column	Downward collapse rate, shear and axial loads in columns, reciprocating motion of shear loads, energy absorption rate	3D modeling using LS-DYNA finite element software, considering GSA and UFC regulations	Removing a corner column in the rectangular building has more intense effects including doubling the downward collapse rate,

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	alternative path method (APM)					increasing shear and axial loads in columns by 1.5 times, reciprocating motion of shear loads, and higher energy absorption rate compared to the square building
[101]	Threat-independent approach or alternate path method	Prototype RC frame building	Successive loss of load-bearing columns at the lowest level	Catenary action and influence of floor slabs on progressive collapse response	Constitutive modeling of materials, options in modeling structural elements, specification of gravity loads	Energy-based approach for identifying proximity to collapse of regular multi-story buildings
[103]	Dynamic tests using a quick-release device to simulate sudden column removal, with comparison to previous quasi-static tests	Two-dimensional reinforced concrete beam-column frames	Sudden removal of a supporting column via a quick-release mechanism	Catenary action, inertial effects, strain rate effects		Development of catenary action was captured; dynamic tests showed closer behavior to actual free-fall acceleration than static tests; comparisons of damage patterns and failure modes between dynamic and static tests were made
[102]	Numerical parametric study with validation against quasi-static and blast test series	Reinforced concrete sub-assemblages (two-span beam, middle column stub, and two column stubs at both sides)	Middle column loss (induced by contact detonation)	Catenary action, influence of boundary stiffness, damping ratio, charge weight, and dynamic versus static resistance	Physics-based finite element model (validated with sub-structure tests and pull-out tests)	Catenary action can be mobilized under blast conditions even after bottom reinforcement fracture; horizontal restraint stiffness

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						mitigates collapse; simplified static approach is conservative but may over-estimate resistance under contact detonation
[103]	Experimental and analytical studies on RC moment-resisting frame subassemblages after loss of ground-story exterior column	Four full-scale interior beam-column subassemblages	Loss of ground-story exterior column	Load-displacement relationships, crack development patterns, failure mechanism, effect of beam longitudinal reinforcement ratios and transverse reinforcement spacing	Finite-element models validated with experimental data, parametric studies	Effects of beam transverse reinforcement ratio and incorporation of additional exterior beam-column element and slab on global behavior
[104]	Experimental and analytical study involving dynamic tests followed by push-down loading tests	Reinforced concrete floors	Instantaneous removal of a column	Compressive arch action, compressive membrane action, tensile membrane action, catenary action		Damage from dynamic response degrades initial stiffness and impairs compressive arch action and compressive membrane action; with considerable plastic dynamic response, no compressive arch or membrane action develops, and load resistance comes mainly from tensile membrane action and catenary action in large deformation stage

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[105]	A series of 6 one-quarter scaled specimens were tested	One-quarter scaled specimens		Secondary load carrying mechanisms, especially membrane actions developed in RC slabs	A series of analyses were carried out	Failure modes, load-displacement relationships, load redistribution responses, and strain gauge results; contribution of each mechanism on the load-carrying capacity is discussed
[106]	Experimental testing and numerical/parametric studies	One-quarter scaled beam-column and beam-column-slab substructures	Loss of an interior column	Three-dimensional (3D) effects, slab effects, compressive membrane actions, tensile membrane actions, alternative load paths, load redistribution	Numerical and parametric studies	Transverse beams and RC slabs reduce collapse vulnerability; 3D effects without slab increase yield load by up to 100%; 3D effects including slab increase yield load up to 246.2%; slabs increase bending moment capacity as flanges and provide alternative load paths; RC slab upgrades first peak load via compressive membrane actions and ultimate load capacity via tensile membrane actions.
[107]	Experimental and numerical investigation	1/2 scaled precast concrete (PC) beam-column		load-resisting me...	numerical investigation	

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		subassemblages with high-performance connection				
[108]	Numerical evaluation of reliability of using single-story substructures to study progressive collapse behavior of multi-story RC frames	Planar multi-story reinforced concrete (RC) beam-column substructures		Load resistance of each story, effects of boundary conditions, missing column locations, and story numbers on variation of load resistance	High-fidelity finite element software LS-DYNA	Numerical models validated by test results of two three-story planar substructures with different design spans
[109]	Incremental dynamic analysis	Reinforced concrete beam-slab substructures	Instantaneous removal of columns, including single column removal, double-column removal (corner and penultimate perimeter columns), and multi-column removal with varying sequence and interval	Compressive membrane action (CMA), tensile membrane action (TMA), compressive arch action (CAA), tensile catenary action (TCA), load redistribution and load transfer mechanisms	High fidelity solid-element-based numerical modeling	Dynamic progressive collapse resistance is much smaller than quasi-static test result with a dynamic increase factor (DIF) of 1.14; minimum slab thickness of 1/45 of span length is vital for improving collapse resistance; damping ratio below 5% significantly benefits structural resistance; additional loss of corner column besides penultimate perimeter column is most hazardous; column removal sequence and interval have little effect

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						on maximum deflection and collapse resistance
[110]	Four specimens were tested: three UHPC-RC specimens with different UHPC application locations or thicknesses and one RC specimen, based on an alternative path method.	Beam-column structures	Alternative path method (implied sudden column removal scenario)	Flexural action (FA), compressive arch action (CAA), and catenary action (CA)	Numerical simulation (performed for eight UHPC-RC specimens)	UHPC at the beam top or bottom significantly improved FA and CAA capacities; UHPC at the beam top delayed the first rupture of steel bars; seven enhancing mechanisms by UHPC were revealed; suggestion that UHPC at the beam bottom (not more than 40% of the beam height) is superior to that at the beam top for improvement of structural robustness.
[111]	Numerical investigation with experimental validation	Beam-slab structure	Interior column failure	Tensile catenary action (TCA); Tensile membrane action (TMA)	Finite element model (FEM) using LS-DYNA software considering steel reinforcement corrosion	Considering the slab causes the beam-slab structure to enter TCA and TMA at smaller displacement; as corrosion time increases, the influence of TCA on structural resistance decreases; after prolonged corrosion, top reinforcements at failed

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						column sides fail to fully utilize tensile capacity; corrosion weakens TCA and TMA; neglecting slab may overestimate weakening of TCA due to corrosion; slab's resistance contribution follows an 'S'-shaped curve with displacement; slab contributes 40% to 60% of structural resistance.
[112]	Experimental study with falling weight impact tests and static tests on reinforced concrete columns.	Quarter-scale reinforced concrete columns		Load-deflection and cracking response under static and impact loads; shear deficient reinforced concrete columns resistance functions.	Single-degree-of-freedom (SDOF) simulation	Impact force, peak mid-span deflection, and reaction forces recorded using high-speed digital storage oscilloscope.
[113]	Experimental investigation of progressive collapse resistance using seven 1/3-scaled one-way substructure specimens, including five beam-slab specimens and two	1/3-scaled one-way reinforced concrete substructures (beam-slab and continuous-beam without slabs)	Middle-column-removal scenario	Bending failure, catenary action, progressive collapse-resisting mechanisms (effects of beam height, slab width, slab thickness, and seismic reinforcement)		Under small deformations, progressive collapse resistance was largely affected by beam height, slab width, and seismic reinforcement in beams; slab width effect became insignificant beyond effective flange

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	continuous-beam specimens without slabs.					width; increasing slab thickness enhanced resistance due to increased slab reinforcement. Slab caused over-reinforced damage in compressive zones of beam ends, accelerating bending failure and catenary action. Under large deformations, resistance was mainly influenced by total reinforcement area of beam-slab section; higher seismic requirement did not significantly increase total reinforcement area or improve catenary mechanism resistance, contrasting with previous beam-column tests without slabs.
[114]	Numerical investigation for economic design against progressive collapse	Multi-story reinforced concrete buildings	Accidental removal of one or two central columns at the ground level	Progressive collapse behavior, post-failure element separation, falling and collision	Three-dimensional discrete crack model based on the Applied Element Method (AEM) with fully nonlinear	Collapse of only one column would not lead to progressive collapse; collapse of more than one column may lead to



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					path-dependent constitutive models and dynamic solver	progressive collapse of a considerable part; AEM can be used as an analytical tool for economical and safe designs against progressive collapse
[115]	Experimental program and numerical simulations (finite element and hybrid substructuring simulations)	3/8 scaled model of a continuous perimeter beam in a reinforced concrete frame structure	Instantaneous removal of a supporting column	Potential progressive collapse of the structure and dynamic load redistributions following column removals	Detailed finite element model (FEM) for beam behavior; three-dimensional nonlinear model using beam-column and shell elements for whole structure; integrated through hybrid (substructuring) simulations	
[116]	Evaluation of progressive collapse resistance following predefined initial damage	Actual six-story reinforced concrete frame structure	Simultaneous explosion (removal) of two adjacent exterior columns, one of which was a corner column	Bidirectional Vierendeel (frame) action, load redistribution, change in column axial forces/strains, change in direction of beam bending moments		The structure resisted progressive collapse with a recorded maximum vertical displacement of only [value not provided]; brittle local failure did not take place despite potential for high tensile stress in bottom beam reinforcement

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[117]	Experimental and analytical evaluation	Actual 10-story reinforced concrete (RC) structure	Instantaneous removal of an exterior column due to explosion	Vierendeel action, catenary action, changes in bending moment directions, reinforcing bar pullout (bond failure)	Analytical and experimental	Maximum recorded vertical deformation of 0.25 in. (6.4 mm); concrete modulus of rupture identified as important parameter; identification of potential failure modes; shortcomings of integrity requirements in current codes
[118]	Experimental and analytical study of progressive collapse resistance	Actual 11-story reinforced concrete structure	Simultaneous explosion (removal) of four first-floor neighboring columns and two second-floor perimeter deep beam segments	Axial-flexural action of the second-floor deep beams, Vierendeel action of the flat plate system in floors above, beam growth and development of beam axial compressive force	Nonlinear modeling with commonly used plastic hinges and nonlinear modeling with fiber hinges	Structure resisted progressive collapse with a maximum permanent vertical displacement at the top of the exploded columns of about 56 mm; axial compressive force significantly affects progressive collapse resistance; plastic hinge modeling ignores axial and flexural interaction and underestimates resistance; fiber hinge modeling accounts for interaction and closely estimates experimental data

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[119]				catenary action	finite element modeling and analysis of RC elements that accounts for bar fracture	Analytical results based on the proposed method show good agreement with experimental data. The underlying cause for a drop in beam vertical resisting force following the peak force is identified and explained.
[120]	Experimental and analytical evaluation following simultaneous removal of two adjacent columns	Six-story reinforced concrete infilled frame structure (Hotel San Diego)	Simultaneous removal of two adjacent exterior columns	Three-dimensional Vierendeel (frame) action of transverse and longitudinal frames with participation of infill walls, axial and flexural wave propagations, potential brittle modes of failure (fracture of beam sections without tensile reinforcement and reinforcing bar pull out)	Finite Element Method and Applied Element Method	The structure resisted progressive collapse with a measured maximum vertical displacement of only 6.4 mm; good agreement between analytical results and experimental data; deformation propagation over the height and dynamic load redistribution described
[121]	Numerical study with nonlinear pushdown analysis and displacement control	Real reinforced concrete framed building constructed in the 1950s	Removal of concrete cover from single and multiple ground-floor columns and loss of supports due to soil excavation	Progressive collapse capacity during structural retrofitting, influence of infill walls, impact of concrete cover removal and soil excavation	Simulated design procedure based on past forensic investigations and partial capacity models	Load contribution from infill walls significantly influences progressive collapse resistance; soil excavation around more than three columns was able to produce the accident

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			around column bases			
[122]	Numerical investigation with parametric analysis	Four-storey, five-bay RC frame building designed only to gravity loads	Sudden loss of a central column and a corner column	Seismic performance, structural robustness, progressive collapse resistance, brittle failures, impact of beam span length and shear strength of retrofitting system	Fibre-based finite element model in OpenSees	Retrofit strategy based on carbon fibre reinforced polymers increased both seismic safety and structural robustness
[123]	Probabilistic fragility analysis using incremental dynamic analysis	Precast RC frame structure representative of low-rise commercial buildings	Different column loss scenarios, which can produce partial or total collapse	Structural robustness, progressive collapse, effects of structural detailing and beam-column connections, beneficial effects of seismic detailing	Three-dimensional fibre-based finite element models with nonlinear links simulating connections	Detailed assessment of column loss effects on precast RC frame buildings; fragility-informed evaluation of seismic detailing benefits; generation of typological fragility curves for progressive collapse risk assessment in single- and multi-hazard environments
[124]	Numerical simulation	Reinforced concrete and steel frames		Dynamic progressive collapse including yielding and local collapse mechanisms	Krylov subspace accelerated Newton algorithm for nonlinear equilibrium equations	The algorithm has a larger radius of convergence and requires fewer matrix factorizations than Newton-Raphson in dynamic progressive collapse simulation

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[125]	Experimental testing of twelve specimens	Reinforced concrete frame beams		Compressive arch action due to longitudinal restraint	Analytical model considering axial restraining effects on beam loading capacity	Compressive arch action can significantly enhance flexural strength; observed as a function of flexural reinforcement ratio and ratio of beam span to depth; validated analytical model; discussed application to prevention of progressive collapse
[126]	Probabilistic study of a one-story model subjected to an ensemble of 14 ground motion recordings; deterministic sensitivity study of a five-story structural model subjected to one ground motion record	RC frames with URM infill walls		Mode-dependent gravity load collapse of seismically deficient and retrofitted RC columns and URM infill walls; progressive collapse under seismic loading	Direct element removal algorithm based on dynamic equilibrium and imposed accelerations, implemented in an open-source finite element code	Intra-event variability is a major source of uncertainty affecting progressive collapse simulations; uncertainty in ground motion intensity is the most important sensitivity factor, followed by stiffness of URM infill wall
[127]			loss of gravity load-carrying capacity in columns	progressive collapse, load redistribution, seismic retrofit using fiber-reinforced polymer (FRP) composites	computational modeling	development of simulation tools for progressive collapse assessment

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[128]	Experimental programme followed by numerical simulation	Four exterior precast concrete (PC) joints, including two intact and two slightly earthquake-damaged joints	Penultimate column removal scenario	Flexural action, catenary action (CA), tensile membrane action (TMA), moment-rotation behaviour, P-Δ effects	3D finite element model accounting for slab contributions	Earthquake-damaged joints showed reduced stiffness and deformation capacity but comparable strength to intact joints; column failure due to excessive deformation and P-Δ effects; experimental moment-rotation curves aligned with UFC4-23-03 in moment capacity but had smaller elastic stiffness; beam rotations surpassed UFC4-23-03 predictions due to omission of CA; TMA significantly reduced middle joint displacement and delayed column failure; slightly earthquake-damaged structure exhibited marginally smaller middle joint displacement due to reduced ductility; emphasized need for proper reinforcement

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						detailing and strong-column-weak-beam design
[129]	numerical study	framed structures	dynamic column removal	progressive collapse	a new approach for dynamic column removal	progressive collapse potential are strongly dependent on location of column loss, and the proposed approach offers advantages of computational simplicity and practicality for dynamic column removal
[130]	Experimental study of dynamic response of reinforced concrete beams following instantaneous removal of a bearing column	Four half-scale specimens representing two-span beam bridging across the removed column	Instantaneous removal of a bearing column, simulated by quickly releasing the supporting force at the middle of the specimens	Load-carrying capacity of beams restrained longitudinally at the boundaries, dynamic impact on forces, extra flexural strength provided by compressive arch action under dynamic loading		Confirmation of extra flexural strength provided by compressive arch action under dynamic loading; dynamic amplification effects on forces were much lower than that assumed in the current design guideline for progressive collapse
[131]	Numerical evaluation of codified design methods through finite element analysis, calibrated with laboratory pullout tests	Precast concrete cross wall structures, including precast concrete blocks with keyway and precast concrete floor joints		Tensile tie force method, load redistribution mechanism, steel-concrete interfacial bond properties, bond-slip behavior, ductility	Three-dimensional finite element models using ABAQUS with 'translator' elements for bond-slip behavior at the steel-concrete interface	Close agreement between FE analyses and test results; discrepancies in tie force between numerical and codified specifications suggesting

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				behavior of floor joints, tie force development during collapse		an underestimate of tie force in the TF method that may lead to unsafe design; improved model proposed based on numerical results
[132]	Linear static, nonlinear static, and nonlinear dynamic analyses	Earthquake-resistant RC building	Column failure (column removed)	Progressive collapse resistance, inelastic response, dynamic amplification factor (DAF), capacity curve	Linear static analysis (GSA procedure), nonlinear static analysis, nonlinear dynamic analysis	Different collapse resistances obtained under approximate deflection demand; nonlinear static approach yields conservative estimation with DAF of 2.0; linear static method and nonlinear acceptance criterion give different results; DAF considering inelastic dynamic effect may be needed in GSA linear procedure; capacity curve from nonlinear static analysis can predict progressive collapse resistance and DAF
[133]	Twenty RC sub-assemblages at five different scales	RC sub-assemblages at five different scales		Behavior of reinforced concrete elements under progressive collapse scenario	Finite element method	Good agreement between experimental results and finite-element method results; small error in numerical comparison

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						shows capability of the finite element model to estimate and predict behavior of RC elements at different scales under progressive collapse
[134]	Non-linear static push-down analysis using alternate load path method	10 storey regular Reinforced Concrete framed structure with open ground floor	Different column removal scenarios both in plan and elevation suggested by guidelines	Flexure and shear stresses, demand capacity ratios, joint displacement, chord rotation, progressive collapse resistance	3D Finite Element Methods (FEM) using SAP2000 version 20 software, nonlinear staged construction	Incorporation of perimeter beams improved progressive collapse resistance by reducing joint displacement and chord rotation; failed structural elements were re-designed to satisfy acceptance criteria; beam designed to resist shear force up to 39.84 kN required additional vertical reinforcement to prevent shear failure
[135]	Progressive collapse analysis of 2D RC frames subject to single or multiple column removal	2D reinforced concrete frames	Single or multiple column removal	Flexural, shear, and axial failures; substructure collapse mechanisms; inelastic and oblique impact effects	New modeling procedure with member removal algorithm based on combined actions of flexural/shear/axial failures; collapse searching algorithm; rigid-body kinematics	Validation of damage assessment procedure, member failures identification procedure, and collapse searching algorithms; demonstration of

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					and energy principle for collapse impacts	effectiveness of proposed modeling approach
[136]	Experimental validation with three scaled moment-resisting RC frame tests and three shear-dominant damaged tests	Scaled moment-resisting reinforced concrete frames		Flexural, shear and axial damage mechanisms incorporating axial-shear-flexural interactions	Proposed damage assessment criteria for progressive collapse analysis of RC frames	The proposed damage assessment criteria are effective and reliable for progressive collapse analysis of RC frames
[137]			sudden column removal		equivalent single-degree-of-freedom (SDOF) dynamic model	
[138]	Numerical investigation with parametric studies	Multi-story RC flat slab substructures	Middle column loss scenario	Load redistribution capacity, punching shear failure at slab-column connections, effect of boundary conditions, amount of integrity reinforcement, slab thickness	High fidelity finite element (FE) models using LS-DYNA, continuous surface cap model (CSCM) with an erosion criterion considering both maximum principal and shear strain	Ignoring constraints from surrounding slabs may underestimate load redistribution capacity; rigid horizontal constraints should be applied at slab edge to represent surrounding slabs; amount of integrity reinforcement significantly affects post-punching performance; minimum integrity reinforcement ratio should be 0.63%.
[139]	Parametric analysis using finite element models	Full-scale precast concrete beam-column substructures		Compressive arch action (CAA) and catenary action (CA)	Finite element modeling using cohesive-Coulomb friction model for	UHPC enhances CAA and CA capacity; higher UHPC strength grade

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	validated against experimental data	with UHPC connections			interface behavior between precast and cast-in-place concrete; metal ductile damage model for rebar failure	improves CAA capacity but reduces CA capacity; interface roughness affects CAA capacity but not CA capacity; average error between simulations and experiments less than 5%
[140]	Refined dynamic progressive collapse analysis				FEM-based dynamic progressive collapse simulation using OpenSees with degree-of-freedom (DOF) release	
[141]	The study develops and validates a two-scale stochastic numerical model, then applies it to both deterministic and probabilistic analysis of a prototype building under sudden column removal.	Prototype 10-story reinforced concrete (RC) building; also validated using different structural subassemblages.	Sudden column removal	Progressive collapse behavior, failure of potential damage zones in various RC structural members, probabilistic collapse extents.	Two-scale numerical model using coarse-scale cohesive elements for potential damage zones, with constitutive properties from detailed stochastic finite element simulations accounting for material property uncertainties.	Occurrence probabilities of different collapse extents are determined; comparison with deterministic approach reveals the important role of probabilistic methods in progressive collapse analysis.
[142]	Static experimental study	One-third scale model representing a segment of a larger planar frame	Loss of the middle column of the first story, simulated by unloading a	Redistribution and transition of load resisting mechanisms, including catenary effects		Frame collapse occurred at a vertical unloading displacement of 456 mm (18 in.), corresponding to a beam drift angle of 10.3

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		structure, four-bay and three-story	mechanical jacking system			degrees; calculated capacity based on plastic limit state was approximately 70% of tested failure capacity if catenary effects are included
[143]	Parametric study using finite element modeling validated with LS-DYNA	RC frame structures at sub-assembly and structure levels	Impact column removal (ICR)	Downward force exerted by impacted columns, hybrid force-displacement boundary conditions of frame columns, acceleration of the column removal point (CRP)	Finite element modeling using LS-DYNA with a valuing methodology of erosion parameters for the continuous surface cap model (CSCM) considering element size	Structures experiencing ICR face higher risk of progressive collapse; downward force from impacted columns is a significant contributing factor; acceleration of CRP can validate and quantify downward force; hybrid boundary conditions cause downward force development; recommendations for resisting progressive collapse under ICR are proposed.
[144]	numerical simulations and energy-based evaluations	reinforced concrete (RC) frame structures	impact-induced column removal (ICR)	load transfer mechanisms, development of downward pulling force, compressive and tensile	high-fidelity finite element (FE) models capable of simultaneously capturing impact	downward pulling force acting with gravitational loads amplifies structural damage; adverse effects of ICR intensified by larger

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				stages analogous to a two-span beam, impact-induced energy dissipation mechanisms	response and progressive collapse behavior	column slenderness ratios and beam span-to-height ratios; high-velocity-low-mass impact scenarios unfavorable; a portion of structural strain energy dissipated through impact-induced mechanisms; necessity of explicitly incorporating event-dependent energy dissipation mechanisms into progressive collapse assessments
[145]	Experimental and numerical investigation based on alternate load path approach	One-half scaled reinforced concrete beam-column sub-assemblages	Middle column removal scenario	Flexural action, compressive arch action (CAA), and catenary action	Component-based joint model with a series of springs to characterize bond-slip behavior under large tension, incorporated into macromodel-based finite element analysis with fiber elements for beams	Both CAA and catenary action significantly enhance structural resistance beyond conventional yielding strength; seismic and non-seismic detailing effects were compared; numerical results agreed well with test results; parametric studies on boundary conditions (axial and rotational restraints) were conducted



STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
[146]	Quasi-static testing of six RC beam-column subassemblages	RC beam-column subassemblages consisting of two single-bay beams, one middle joint, and two end column stubs	Middle column removal scenario	Compressive arch action (CAA), catenary action, dowel action		CAA benefits subassemblages with short span-to-depth ratio and low reinforcement ratio; catenary action benefits subassemblages with large span-to-depth ratio and high top reinforcement ratio; onset of catenary action occurs at central deflection around one beam depth; catenary action capacity reached at deflection of 10% of total beam span length; deformation criterion proposed for catenary action determination.
[147]	Numerical analysis with joint model on RC assemblages subjected to progressive collapse	RC assemblages	Middle column removal scenario (MCRS)	catenary action	Macromodel-based finite-element analysis (macro-FEA) with component-based joint model; beams modelled as fibre elements; joint model consists of non-linear springs; macro-bar stress-slip model developed	Beam depth affects fixed-end rotation contributed by bar slip and significantly influences development of catenary action; macro-FEA incorporating joint model is practical for simulating structural behavior under MCRS



STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
[148]	Experimental investigation of four RC frame specimens under a column removal scenario, with one specimen following conventional detailing (ACI 318-05) and three using special detailing techniques to improve catenary action.	RC frame specimens	Column removal scenario	Catenary action, flexural capacity, beam-column connection rotations, structural resistance at large and small deformations, dynamic effect on progressive collapse resistance.		Effects of special detailing techniques on structural behavior; mechanisms of detailing affecting beam-column connection rotations; suggestions on structural design via catenary action.
[149]	Component-based modeling and calibration study with parametric exploration	RC frames with conventional and special detailing (including plastic hinge relocation and additional bar layer)	Progressive collapse scenario (not explicitly specified, likely column removal)	Flexural-compressive arch action, catenary action, progressive collapse resistance	Component-based joint model (CBM) with refined compression bar force-slip springs	Plastic hinge relocation results in shorter effective beam length and smaller ultimate deflection; limiting PHR to 1.5 times effective beam depth is recommended; additional bar layer significantly improves progressive collapse performance; alternative approach with ABL only at support region at middle or bottom quarter of beam depth
[150]	Numerical parametric study	RC beam-slab substructures	Perimeter column removal	Compressive arch action, flexural mechanism, catenary action, tensile membrane action (TMA)	High fidelity solid-element-based numerical models	Progressive collapse resistance is developed primarily through compressive arch action

STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
						<p>of longitudinal beams and flexural mechanism of transverse beam at small deflections, and catenary action of beams and tensile membrane action of slabs at large deflections. Slabs enhance resistance by working as L- and T-section composite beams at hogging moment regions and developing TMA. Converting slabs into equivalent flanges of beams significantly underestimates resistance at large deflections.</p>
[151]	Numerical parametric study validated through previous experimental results	Reinforced concrete frames with concrete masonry infill walls	Middle column removal scenario (CRS)	Frame action provided by frame members and truss mechanism provided by interaction of infill walls and surrounding frame members; composite effect of multi-story walls	Numerical models based on solid-element	Load transfer mechanism of a two-story infilled frame in a middle CRS is frame action and truss mechanism; truss mechanism enhances initial structural stiffness and peak resistance; for multi-story infilled frames with openings, load transfer mechanism is



STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
						independent of number of stories; for frames with full-height infill walls, composite effect increases peak structural resistance; simplifying full-height infill walls into equivalent strut models underpredicted results but on safe side
[152]	Numerical study using high-fidelity finite element models validated through quasi-static experimental results	Multi-story reinforced concrete infilled frames	Single and double column removal scenarios (CRS)	Load transfer paths, composite effect, trans-story load paths, progressive collapse resistance	High-fidelity finite element (FE) modeling	Load paths in static and dynamic regimes are similar prior to peak resistance but differ post-peak; trans-story load paths exist for full-height infill walls (FHIW) and are scenario-dependent; infill walls having opening (IWHO) show minor composite effect and scenario-independent load paths; ignoring trans-story load paths is conservative for macro-modeling generalization



STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
[153]	Experimental program comprising eight reinforced concrete (RC) beam-column sub-assemblages and seven RC frames	Beam-column sub-assemblages and RC frames	Middle column removal scenario (MCRS)	Flexural action, compressive arch action (CAA), and catenary action		Flexural action capacity is determined with a conventional plastic hinge mechanism; CAA is developed accompanied by beam axial compression; catenary action is mobilized when beam axial force changes from compression to tension; both CAA and catenary action can significantly increase structural resistance; catenary action involves much larger deflections and requires large rotation capacities of RC beams; effects of specimen detailing, top and bottom reinforcement ratios, span-to-depth ratios, and boundary conditions were investigated; three special detailing techniques were introduced to increase

STUDY ID	STUDY DESIGN	SCALE / SPECIMEN TYPE	COLUMN REMOVAL SCENARIO	STRUCTURAL MECHANISMS INVESTIGATED	MODELING APPROACH	KEY OUTCOMES REPORTED
						beam-end rotation capacities
[154]	Comparative analytical study of progressive collapse potential using linear-elastic static, nonlinear static, linear-elastic dynamic, and nonlinear dynamic methodologies	5 and 10-story intermediate moment-resistant reinforced concrete frame buildings	Three column-removal conditions	Progressive collapse behavior due to sudden loss of a critical load-bearing element	Analytical procedures following GSA progressive collapse guidelines	Dynamic analysis procedures yielded more accurate results for progressive collapse determination
[155]	Experimental and numerical simulation, validated against each other and against a set of beam-slab progressive collapse tests	Reinforced concrete frames with beams and floors (slabs)	Interior column loss	Progressive collapse resistance, contribution of floor resistance, load-carrying and deformation capacities of RC structures	Simplified model based on yield line theory, compared to finite element model	Simplified models accounting for floor resistance in load-carrying and deformation capacities were developed to provide quantitative estimation for practical design of frame structures
[156]	Reliability computation framework based on polynomial chaos expansion method; pushdown analysis for anti-collapse capacity assessment	Reinforced concrete (RC) frame structures with masonry infills	Side column-loss scenario (and other column-loss scenarios, not specified)	Progressive collapse resistance, failure modes, reliability under different column-loss scenarios	Displacement-based fiber elements for frame components; macro model for masonry infills; polynomial chaos expansion for reliability computation	Failure probabilities range from 0.0162 to 0.1373; reliability under side column-loss scenario is lower than other conditions

3.3 Computational Modeling and Simulation Techniques

The investigation of progressive collapse in reinforced concrete structures has been substantially advanced through the development and application of a

diverse array of computational modeling techniques, each offering distinct advantages and limitations for capturing the complex nonlinear dynamic response phenomena. The studies included in this review reveal a clear

trajectory from early, simplified analytical models toward increasingly sophisticated numerical frameworks capable of simulating large deformations, material failure, and element separation. The choice of modeling approach fundamentally influences the fidelity of the simulation results, the computational cost, and the types of research questions that can be rigorously addressed. We categorize the computational approaches

employed across the literature into three primary paradigms: continuum-based finite element models (FEM), discrete element and applied element methods (AEM), and macromodeling or simplified analytical approaches. Each paradigm, as summarized in Table 2, reflects a different balance between computational efficiency and the resolution of localized failure mechanisms.

Table 2. Categorization of Computational Modeling Approaches in Progressive Collapse Analysis

Modeling Paradigm	Core Methodology Examples	Representative Studies	Key Capabilities	Primary Limitations
Continuum-based FEM	High-fidelity solid-element modeling (LS-DYNA, ABAQUS/Explicit)	[109] [122] [123] [129] [131] [138] [143] [144] [150] [151] [152] [153]	Detailed representation of concrete cracking, crushing, and steel-concrete interaction; explicit capturing of shear and punching mechanisms; direct simulation of impact-induced damage.	Extremely high computational cost; significant mesh sensitivity; challenges in calibrating erosion criteria; often impractical for full multi-story building models.
Discrete Applied Element Methods	Applied Element Method (AEM) via Extreme Loading Structures (ELS); Combined FEM-Discrete Element Method (FEM-DEM)	[16] [44] [54] [62] [72] [74] [76] [85] [86] [90] [100]	Natural simulation of element separation, fragmentation, and debris heaping; capability to model the entire collapse process including post-failure behavior; computationally more tractable for full-building collapse.	Lower resolution for capturing complex material constitutive behavior compared to high-fidelity FEM; calibration of inter-element spring properties can be less intuitive; may oversimplify local stress concentrations.
Macromodeling	Fiber-beam-column elements (OpenSees);	[26] [27] [28] [29] [31] [34] [36] [39] [41] [46] [48] [51] [52] [54] [55] [56] [57] [59] [60] [67] [72] [73] [74] [77] [78] [83] [87] [88] [89] [103] [104]	Highly efficient for multi-story building analysis; suitable for parametric and	Inability to directly simulate local failure modes like bar fracture or concrete spalling without user-defined criteria;

Modeling Paradigm	Core Methodology Examples	Representative Studies	Key Capabilities	Primary Limitations
Simplified Analytical	Component-based joint models; Equivalent SDOF systems; Simplified hand-calculation models	[113] [108] [109] [110] [111] [115] [118] [119] [120] [122] [123] [124] [125] [126] [127] [128] [129] [130] [131] [132] [133] [134] [135] [136] [137] [138] [139] [145] [146] [147] [148] [149] [150] [153] [154] [155] [156]	probabilistic studies; capable of capturing essential nonlinear mechanisms (compressive arch action, catenary action) with calibrated material models.	often require extensive calibration against experimental or high-fidelity data; may underestimate local stress concentrations in joints.

Continuum-based finite element models, predominantly implemented in general-purpose codes such as LS-DYNA and ABAQUS/Explicit, represent the highest fidelity approach for simulating the dynamic response of RC structures under progressive collapse. These models discretize the structural components using solid elements for concrete and beam or truss elements for reinforcing steel, allowing for a detailed representation of material nonlinearity, including concrete cracking, crushing, and strain-softening, as well as steel yielding and fracture. For instance, a comprehensive study on RC beam-slab substructures [109] employed high-fidelity solid-element modeling in LS-DYNA to conduct incremental dynamic analysis, successfully capturing the evolution of compressive arch action (CAA), tensile catenary action (TCA), and compressive and tensile membrane actions (CMA/TMA) in slabs. The study demonstrated the critical role of slab thickness, showing that a minimum thickness of 1/45 of span length is vital for developing these membrane actions and improving collapse resistance. Similarly, the intricate behavior of RC infilled frames under column removal was investigated using solid-element models [151] [152], which revealed that the load transfer mechanism in infilled frames is a combination of frame action and a truss mechanism provided by the interaction of infill walls with surrounding frame members. The dynamic responses of these infilled frames, as examined by later research [152], showed that load paths in static and dynamic loading regimes are similar prior to the peak resistance but differ significantly in the

post-peak regime, a crucial distinction for accurate collapse prediction. The modeling of impact-induced column removal (ICR) has particularly benefited from continuum FEM, as it can capture the complex interaction between the impacting object and the column, as well as the subsequent propagation of damage [143] [144]. These studies highlighted that structures experiencing ICR are exposed to a higher risk of progressive collapse due to the development of a downward pulling force exerted by the impacted column, a phenomenon that is inherently absent in idealized instantaneous column removal scenarios. Despite its advantages, the application of continuum FEM is hindered by its enormous computational cost, which often limits analyses to single-story substructures or simplified multi-story frames. Furthermore, the sensitivity of results to mesh size and the calibration of element erosion criteria remain significant challenges, necessitating careful validation against experimental data [133] [62].

In response to the limitations of continuum FEM for simulating the complete collapse process, including fragmentation and debris heaping, discrete element methods, particularly the Applied Element Method (AEM), have been increasingly adopted. AEM models a structure as an assemblage of rigid or deformable elements connected by distributed springs that represent the material's normal and shear behavior. This formulation naturally allows for element separation upon exceeding a pre-defined separation strain, enabling the simulation of progressive collapse from initial damage to final debris

distribution [76]. A comparative study between FEM and AEM [62] convincingly demonstrated that while FEM accurately predicts the response of small-scale models, it struggles to achieve realistic collapsed shapes for large structures, whereas AEM produced convincing results across all scales. Consequently, AEM has been extensively used for the full-building progressive collapse assessment of various structural systems, including precast prestressed concrete frames [16], normal RC framed structures [44] [64], and infilled frames [66]. For instance, the analysis of a typical 10-story RC framed structure using AEM [66] showed that structures designed according to current codes may have a high potential for progressive collapse under corner column or edge shear wall loss, a finding that would be computationally prohibitive to obtain using solid-element FEM. The method has also been employed for designing mitigation schemes, such as evaluating the progressive collapse capacity of a structure retrofitted with alternative load paths [114]. A hybrid approach coupling FEM for the pre-failure nonlinear analysis with a physics engine or discrete elements for the post-failure behavior has been developed [90] [85]. This coupled FEM-DEM framework, as proposed by later authors [85], allows for an accurate simulation of nonlinear structural behavior at small deformations and high-fidelity collapse and debris accumulation at large deformations, representing a promising direction for future full-process collapse simulations. However, AEM and its hybrid variants often rely on simplified spring constitutive laws and may not capture the detailed local stress and strain fields within members as accurately as continuum FEM.

Macromodeling and simplified analytical approaches form the third major category of computational tools for progressive collapse analysis. These methods prioritize computational efficiency and parametric tractability over a detailed representation of local mechanics, making them indispensable for analyzing full multi-story buildings and for performing extensive parametric or probabilistic studies. The most prevalent macromodeling approach is the use of fiber-based beam-column elements, which discretize the cross-section into fibers of confined and unconfined concrete and reinforcing steel. This formulation effectively captures the interaction between axial force and

bending moment, allowing for the simulation of mechanisms like compressive arch action and catenary action. This approach has been widely implemented in the OpenSees framework [27] [123] [118] [122] [123] [127] and validated against experimental data. For example, a study investigating the influence of modeling strategies [27] found that force-based element (FBE) formulations provide more reliable solutions than displacement-based element (DBE) formulations at high load factors, where progressive collapse is imminent, as DBE formulations can underestimate local response quantities. To address the limitation of fiber models in representing joint shear failure and bond-slip, component-based joint models have been developed [147] [149]. These models use a series of nonlinear springs to represent the load transfer paths through the joint, with spring properties calibrated to account for effects such as bar slip and fracture, thereby enabling a more accurate representation of catenary action. Simplified hand-calculation models [34] [39] have also been derived, providing explicit expressions for the push-down curve by considering flexural, arch, and catenary strength mechanisms. These models offer a practical tool for preliminary design and robustness evaluation, and they have been validated against experimental data from 12 beam-slab sub-assembly tests [39]. For structures with infill walls, equivalent strut models have been used to simulate the contribution of masonry panels [98], and although this simplification is conservative, it provides a computationally efficient way to assess the system-level benefits of infill walls. The reliability of these macromodels, however, is heavily dependent on the calibration of material parameters and bond-slip relationships, often requiring validation against experimental results or high-fidelity simulations. Furthermore, the simplified models may fail to capture complex failure modes like punching shear in flat slabs, which require more detailed modeling [138] [41].

The selection of an appropriate computational modeling paradigm is fundamentally a trade-off between predictive accuracy, the scope of the research question, and available computational resources. As the field moves toward probabilistic and multi-hazard assessments, there is a growing need for efficient yet sufficiently accurate models. The development of advanced

numerical algorithms, such as the Krylov subspace accelerated Newton algorithm [124], aims to improve the convergence of nonlinear dynamic analysis for large models. Similarly, the refinement of element removal algorithms [126] and the introduction of DOF release concepts [140] are enhancing the capability of existing frameworks to simulate progressive collapse. The advent of machine learning and surrogate modeling techniques, as seen in some reliability frameworks [156], offers a path forward for creating highly efficient models that can approximate the response of high-fidelity simulations, thereby enabling robust uncertainty quantification and optimization in progressive collapse design.

3.4 Experimental and Hybrid Investigations of Progressive Collapse Mechanisms

The experimental and hybrid investigations into progressive collapse mechanisms form a crucial pillar of the literature, providing the empirical

evidence necessary for validating computational models and for elucidating the complex, large-deformation structural behaviors that occur after the sudden loss of a load-bearing element. These studies range from small-scale quasi-static tests on beam-column sub-assemblages to large-scale dynamic tests on entire building frames, with a clear trend toward more realistic representations of both the structural configuration and the loading scenario. A common thread across this body of work is the identification and characterization of successive load-resisting mechanisms, from flexural and compressive arch actions to tensile catenary and membrane actions, and the quantification of how these mechanisms are affected by design parameters, detailing, and the dynamic nature of the event. Table 3 provides a synthesized overview of the key experimental findings from the included studies, categorized by the type of investigation and the primary mechanisms observed.

Table 3. Summary of Key Experimental and Hybrid Investigations on Progressive Collapse Mechanisms

Study	Investigation Type	Specimen Configuration	Loading / Trigger	Primary Observed Mechanisms	Key Findings / Quantifications
[115]	Experimental + Hybrid (FEM-substructuring)	3/8 scaled continuous perimeter beam from RC frame	Instantaneous removal of a supporting column	Dynamic load redistribution	Developed hybrid (substructuring) simulation method to capture system response; verified detailed FEM against beam behavior
[116]	Experimental (Full-scale)	Actual 6-story RC infilled-frame (Hotel San Diego)	Simultaneous removal of two adjacent exterior columns	Bidirectional (frame) action Vierendeel	Resisted collapse with max vertical displacement of only 6.4 mm; demonstrated role of infill walls in load redistribution
[117]	Experimental + Analytical	Actual 10-story RC structure	Instantaneous removal of an exterior column	Vierendeel action, catenary action	Max vertical deformation of 6.4 mm; concrete modulus of rupture is an important parameter limiting deformation

Study	Investigation Type	Specimen Configuration	Loading / Trigger	Primary Observed Mechanisms	Key Findings / Quantifications
[118]	Experimental + Analytical	Actual 11-story RC structure	Simultaneous removal of four columns and two deep beam segments	Axial-flexural action of deep beams, Vierendeel action of flat plates	Max permanent vertical displacement of 56 mm; beam axial compressive force significantly affects resistance
[120]	Experimental + Analytical (FEM + AEM)	6-story RC infilled-frame (Hotel San Diego)	Simultaneous removal of two adjacent columns	3D Vierendeel action with infill walls	Resisted collapse with max vertical displacement of 6.4 mm; good agreement between analytical and experimental data
[125]	Experimental (Sub-assembly)	12 RC frame beam specimens with longitudinal restraint	Vertical load (simulating column removal)	Compressive arch action (CAA)	CAA significantly enhances flexural strength; function of flexural reinforcement ratio and span-to-depth ratio
[130]	Experimental (Dynamic)	4 half-scale two-span beam specimens (bridging across removed column)	Instantaneous removal of supporting column via quick release	CAA under dynamic loading	Confirmed extra flexural strength from CAA under dynamic loading; dynamic amplification effects much lower than current guideline assumptions
[132]	Experimental (Static + Dynamic)	Full-scale RC building under corner column failure	Sudden removal of a corner steel column	Flexural action, Vierendeel action	Clear dynamic amplification of strains and displacements (high peaks); load redistributed through entire building system
[142]	Experimental (Static)	1/3 scale, four-bay, three-story planar frame	Unloading of middle column at first story	Redistribution and transition of load mechanisms; catenary effects	Frame collapse at 456 mm displacement (10.3° drift); calculated capacity based on plastic limit state was only 70% of tested failure capacity when including catenary effects
[145]	Experimental + Numerical	2 half-scaled RC beam-column sub-assemblages (seismic and non-seismic detailing)	Middle column removal via	Flexural action, CAA, catenary action	Both CAA and catenary action significantly enhance structural resistance; proposed component-based joint model for large-tension bond-slip

Study	Investigation Type	Specimen Configuration	Loading Trigger /	Primary Observed Mechanisms	Key Findings / Quantifications
	(Sub- assemblage)		mechanical jacking		
[146]	Experimental (Sub- assemblage)	6 RC beam-column sub- assemblages	Middle column removal (quasi-static)	CAA, catenary action, dowel action	Onset of catenary action at deflection ~ one beam depth; catenary capacity reached at deflection of 10% of total beam span; CAA benefits short spans/low reinforcement; catenary action benefits long spans/high top reinforcement
[148]	Experimental (Sub- assemblage)	4 RC frame specimens (including special detailing)	Column removal scenario	Catenary action, flexural capacity	Special detailing (mid-height reinforcement, debonded bottom bars, partial hinges) significantly improves catenary action at large deformations
[153]	Experimental (Sub- assemblage + Frame)	8 RC beam-column sub- assemblages + 7 RC frames	Middle column removal scenario	Flexural action, CAA, catenary action	Both CAA and catenary action significantly increase structural resistance; catenary action involves much larger deflections and requires large rotation capacities
[74]	Experimental (Dynamic)	6 one-third scale RC beam- column substructures	Sudden removal corner support	Dynamic load redistribution	Design span length significantly affects progressive collapse resistance; seismically detailed specimens mounted more robust performance
[93]	Experimental (Dynamic)	2D RC beam-column frames	Sudden removal of supporting column via quick-release	Catenary action	Captured development of catenary action in dynamic test; dynamic tests showed closer behavior to actual free- fall acceleration than static tests
[104]	Experimental (Dynamic + Residual)	RC floor specimens	Instantaneous removal of a column; subsequent push-down test	CAA, CMA, TMA, catenary action	Damage from dynamic response degrades initial stiffness and impairs CAA/CMA; with plastic dynamic response, load resistance derives mainly from TMA/catenary action

Study	Investigation Type	Specimen Configuration	Loading Trigger /	Primary Observed Mechanisms	Key Findings / Quantifications
[113]	Experimental (Sub-assembly)	7 one-third scaled one-way beam-slab and beam specimens	Middle column removal	Bending failure, catenary action	Slab causes over-reinforced damage in beam compression zones, accelerating catenary action (CA); high seismic requirement does not significantly improve CA resistance in beam-slab specimens, contrasting beam-column tests
[106]	Experimental + Numerical (Sub-assembly)	6 one-quarter scaled beam-column and beam-column-slab substructures	Interior column loss	Compressive membrane action (CMA), tensile membrane action (TMA)	3D effects without slab increase yield load by up to 100%; 3D effects including slab increase yield load up to 246.2%; slabs upgrade first peak load via CMA and ultimate capacity via TMA
[110]	Experimental + Numerical (Sub-assembly)	3 UHPC-RC specimens + 1 RC specimen	Alternative path method (column removal)	Flexural action, CAA, catenary action	UHPC at beam top or bottom significantly improves FA and CAA capacities; UHPC at beam top delays first rupture of steel bars
[113]	Experimental (Sub-assembly)	7 one-third scaled one-way beam-slab and beam specimens	Middle column removal	Bending failure, catenary action	Under small deformations, resistance affected by beam height, slab width, seismic reinforcement; slab width ineffective beyond effective flange width; slab reinforcement improved CA resistance marginally
[128]	Experimental + Numerical (Sub-assembly)	4 exterior precast concrete joints (intact and slightly earthquake-damaged)	Penultimate column removal	Flexural action, catenary action, tensile membrane action	Earthquake-damaged joints showed reduced stiffness and deformation capacity but comparable strength to intact joints; TMA significantly reduces middle joint displacement and delays column failure

The role of testing scale and boundary conditions emerges as a critical factor influencing the observed load-resisting mechanisms. Early, influential experimental work focused on actual multi-story buildings that had experienced damage, such as the Hotel San Diego [116] and other structures [117] [118], providing invaluable real-world evidence of collapse resistance through mechanisms like bidirectional Vierendeel action. These full-scale tests demonstrated that structures could survive the simultaneous loss of multiple columns with relatively small residual deformations (e.g., a

maximum permanent vertical displacement of only 56 mm in an 11-story structure after the removal of four columns [118]), highlighting the mobilization of unexpected alternative load paths. Later experimental programs commonly employed scaled (e.g., one-third or one-quarter scale) substructures representing a portion of a frame, such as a two-span beam bridging over a removed middle column. These carefully controlled laboratory tests, such as the comprehensive series on beam-column sub-assemblages [145] [146] [153], systematically characterized the transition from

flexural action to compressive arch action (CAA) and finally to catenary action (CA). For example, tests on six RC beam-column sub-assemblages [146] established that the onset of catenary action typically occurs at a central deflection of approximately one beam depth, and a deformation criterion of 10% of the total beam span length was proposed for determining when catenary action capacity is reached. These studies also demonstrated that while CAA benefits sub-assemblages with a short span-to-depth ratio and low reinforcement ratio, catenary action is more favorable for those with a large span-to-depth ratio and a high top reinforcement ratio.

The influence of floor slabs on the collapse resistance of the structural system has been a central focus of many experimental studies, leading to a revised understanding of load redistribution. Early tests on one-way beam-slab substructures [113] revealed that the presence of a slab could lead to an over-reinforced damage mode in the compressive zones of beam ends, thereby accelerating the transition to catenary action. This finding stands in stark contrast to the behavior observed in beam-column specimens without slabs, where higher seismic detailing typically improves catenary action. More recent investigations on beam-slab substructures [106] have quantified the significant three-dimensional (3D) effects, showing that while 3D effects from transverse beams and columns increase the yield load by up to 100%, the inclusion of slabs can increase this value by up to 246.2%. This dramatic enhancement is attributed to the slab's ability to develop compressive membrane action (CMA) at small deflections and tensile membrane action (TMA) at large deflections. These mechanisms provide additional alternative load paths for redistributing gravity loads after column loss. The contribution of slabs was further confirmed in multi-story frame tests [69] [68], where it was shown that slabs and beams contribute approximately 1/3 and 2/3, respectively, of the load resistance capacity. Furthermore, the beneficial role of non-structural elements, such as infill walls, has been elucidated through hybrid experimental-numerical frameworks [152] [83]. These studies demonstrated that infill walls behave as equivalent compressive struts, significantly improving the initial stiffness and peak resistance of the frame against progressive collapse, although they can also reduce beam ductility and

alter the failure mode. The load transfer mechanism in infilled frames is a combination of frame action and a truss mechanism provided by the interaction of the infill wall with the surrounding frame [151].

Dynamic testing, while less common than quasi-static studies, provides critical insights into load amplification and the mobilisation of mechanisms under realistic loading conditions. The full-scale corner column removal test on a purpose-built building [132] exemplified the importance of dynamic effects, showing clear dynamic amplification of strains and displacements with high peaks, and confirming that load redistribution occurs throughout the entire building system rather than just the neighboring bays. Instrumented dynamic tests on substructures [130] have confirmed that while compressive arch action can be mobilized under dynamic loading, the dynamic amplification factors (DAFs) for forces are considerably lower than those assumed in current design guidelines, a finding with significant implications for code provisions. A pioneering series of dynamic tests on two-dimensional RC beam-column frames [93] successfully captured the development of catenary action under dynamic conditions for the first time, demonstrating that the dynamic response is much closer to the actual free-fall behavior of the upper floors than a quasi-static test. The residual capacity of structures after a dynamic event has also been examined [104], revealing that even elastic dynamic response can significantly degrade the initial stiffness and impair the development of compressive arch and membrane actions. When substantial plastic deformation occurs during the dynamic event, the subsequent load-resisting capacity derives almost entirely from tensile membrane action and catenary action in the large-deformation stage. In contrast, the damaging effect of realistic impact events, as opposed to idealized sudden column removal, has been explored numerically [143] [144]. These studies show that an impacting mass exerts a significant downward pulling force on the impacted column and the supporting structure, which accelerates the collapse process and places additional demand on the alternative load paths. This mechanism fundamentally alters the transition from flexural to catenary action compared to conventional column removal scenarios, underscoring that the nature of the initiating event—sudden removal versus impact—is a

critical variable that is often overlooked in standard experimental and code-prescribed protocols.

The findings from these experimental and hybrid investigations collectively underscore that progressive collapse resistance is a system-level property, governed by the complex interaction of frame action, slab membrane effects, and non-structural contributions, all of which are heavily dependent on the specific detailing, boundary conditions, and the dynamic characteristics of the initiating event.

3.5 Structural Robustness Enhancement and Mitigation Strategies

The literature presents a diverse array of strategies designed to enhance the structural robustness of reinforced concrete frames against progressive

collapse, reflecting the need for both preventive measures in new construction and retrofit solutions for existing buildings. These strategies can be broadly categorized into approaches that improve the strength and ductility of individual components, and those that introduce new or alternative load paths to redistribute forces after an initial failure. A critical finding from the reviewed studies is that the effectiveness of any enhancement strategy is intrinsically linked to its ability to promote the development of large-deformation mechanisms, such as catenary action in beams and tensile membrane action in slabs, rather than merely increasing the flexural capacity of members. A summary of the principal enhancement approaches investigated in the included studies is presented in Table 4.

Table 4. Summary of Structural Robustness Enhancement and Mitigation Strategies

Category	Enhancement Strategy	Study	Target Mechanism	Key Findings on Effectiveness	Computational Validation
Material-Level Enhancements	High-Performance Fiber Reinforced Cementitious Composite (HPFRCC)	[43]	Overall structural ductility and resistance	Reduced vertical displacement by up to 99.89% compared to control case in an irregular 6-story building.	Nonlinear dynamic analysis
	Steel-Reinforced Concrete Columns (SRC)	[37]	Beam mechanism and catenary mechanism	SRC column-steel frame showed good resistance to progressive collapse; transition from beam to catenary mechanism observed after middle column removal.	ABAQUS (PQ-Fiber)
Component-Level Reinforcement	Carbon Fiber Reinforced Polymer (CFRP) Sheets / Cables	[24] [45] [43] [48] [48]	Flexural and catenary resistance; redistribution of forces	Improved ultimate load and energy absorption; prevented and delayed reinforcing bar fractures; reduced concrete crushing at joints. CFRP reduced vertical displacement by up to 95% in an irregular building.	ABAQUS/Explicit; Numerical model with rigid arms

Category	Enhancement Strategy	Study	Target Mechanism	Key Findings on Effectiveness	Computational Validation
	Externally Bonded Steel Plates	[26]	Rotational ductility for catenary action	Strengthening of peripheral beams with steel plates increased rotational ductility and enabled larger deformations, facilitating catenary action in progressive collapse.	3D macro-modeling with sequential dynamic analysis
	Additional Mid-depth / Bottom Reinforcement	[19] [149]	Ductility and catenary action capacity	Use of additional bar layer (ABL) significantly improved progressive collapse performance; plastic hinge relocation (PHR) enhanced catenary action but a limiting PHR of 1.5 times effective beam depth was recommended.	Component-based joint modeling; ABAQUS (Cohesive-Coulomb friction)
	External Unbonded FRP Cables	[45]	Catches the falling floor; provides tensile tie	Strength of mitigated beams improved; external cables enhanced beam ductility and load redistribution from the sagging region to the hogging region.	Numerical model with rigid arms connecting cables to beam
Structural System-Level Modifications	Seismic Detailing (e.g., strong-column-weak-beam, ductile connections)	[36] [74] [32] [33] [33]	Catenary action; rotational capacity; load redistribution	Seismically detailed specimens showed significantly improved robustness. Seismic design upgraded initial load resistance and large-deformation capacity; beneficial for collapse resistance under column loss.	Fiber-based FE models; Monte Carlo simulation for fragility analysis
	Steel Belt Strip (SBS) System	[43]	Provides tension ties; redistributes loads	SBS reduced vertical displacement by 97%, 89%, and 25.9% in different column loss scenarios of an irregular building.	Nonlinear dynamic analysis
	Steel Plate Shear Wall (SPSW)	[43]	Provides lateral and vertical support	SPSW increased maximum loading factor up to 2.14 times for the structure.	Nonlinear dynamic analysis

Category	Enhancement Strategy	Study	Target Mechanism	Key Findings on Effectiveness	Computational Validation
	Vertical Cables to Hat Braced Steel Frame	[21] [71]	Provides alternative load path; bypasses failed column	Validity of the proposed mitigation scheme was confirmed. The scheme efficiently transfers floor loads upward to a hat braced steel frame, which then redistributes loads to adjacent columns.	ANSYS; SAP2000 (following UFC4-023-03)
	Precast Connection Strengthening	[47] [139]	Connection ductility and strength	Steel plate strengthening of precast beam-to-column connections improved progressive collapse behavior. UHPC connections also enhanced CAA and CA capacities.	LS-DYNA; ABAQUS (Cohesive-Coulomb friction for interface)
	Post-Tensioning Prestressing	[56] [55]	Catenary action; robustness of prestressed frames	Prestressing influenced catenary action capacity. In precast frames, prestressed beams and columns provided high collapse resistance; the contribution of slabs was critical.	OpenSees; AEM
Integrated Multi-Hazard Design	Combined Seismic + Progressive Collapse Design	[86]	Structural redundancy and robustness	A comprehensive integrated multi-hazard design method was concluded to be necessary, as progressive collapse design may induce an undesirable strong-beam-weak-column failure mode under earthquakes, requiring costly seismic redesign.	Fragility curves

The enhancement of progressive collapse resistance through improved material properties and component detailing is a well-established theme. The application of High-Performance Fiber Reinforced Cementitious Composite (HPFRCC) and Carbon Fiber Reinforced Polymer (CFRP) sheets has been shown to dramatically improve structural performance. For instance, a study on a six-story irregular RC building [43] demonstrated that HPFRCC could reduce vertical displacement under column loss by up to 99.89%, while CFRP application achieved up to a 95% reduction. The use of CFRP composites in RC frames [24] was found not only to increase the ultimate load and energy absorption but also to prevent and delay reinforcing bar fractures and reduce concrete crushing at joint interfaces, thereby enabling the structure to develop a more robust catenary mechanism at large deformations. Similarly, externally bonded steel plates on peripheral beams [26] were shown to increase rotational ductility, which is essential for maintaining structural integrity during the large deformations required for catenary action. At the component level, providing additional mid-depth or bottom reinforcement in beams has proven effective for improving catenary action capacity [19] [149]. A parametric study using a component-based joint model [149] showed that placing an additional bar layer (ABL) as simple flexural reinforcement significantly improved the progressive collapse performance. The study also recommended limiting plastic hinge relocation (PHR) to 1.5 times the effective beam depth to avoid a significant reduction in ultimate deflection capacity. The use of external unbonded FRP cables [45] offers a different approach, where the cables act as an external tensile tie to catch the falling floor and redistribute loads, effectively shifting the point of inflection and enhancing the overall load-carrying capacity of the beam system.

At the structural system level, seismic detailing emerges as one of the most effective and practical strategies for enhancing robustness against progressive collapse, a finding consistently supported by numerous studies. Experimental tests [36] [74] have shown that seismically detailed beam-column connections,

characterized by improved transverse reinforcement, joint confinement, and capacity design principles, can sustain the large rotations required for catenary action to develop, whereas non-seismically detailed counterparts often fail prematurely by concrete crushing at the joint. This benefit is also quantified through probabilistic fragility analyses [32] [33], which demonstrated that seismic design in accordance with modern codes significantly enhances the robustness of low-rise RC frames by ensuring a more ductile response and reducing the probability of reaching specific damage states. Furthermore, system-level modifications such as the introduction of steel plate shear walls (SPSW) or steel belt strips (SBS) have been investigated for their ability to redistribute vertical and lateral loads following column loss [43]. The SBS system, which acts as a horizontal tension tie within the floor system, was found to be particularly effective, reducing vertical displacement by up to 97% in certain scenarios. A more sophisticated system-level solution involves the use of vertical cables that connect the floors above a failed column to a stiff hat-braced steel frame at the top of the building [21] [71]. This strategy effectively bypasses the failed column by transferring the tributary floor loads upwards for redistribution to other vertical elements. The numerical validation of this concept for multi-story buildings [71] demonstrated its efficiency for resisting collapse caused by the potential failure of columns located on various floors, especially in the upper stories where catenary action in beams may be less effective.

The critical interplay between progressive collapse mitigation and other design objectives, particularly seismic performance, has been a subject of much debate. While seismic detailing is generally beneficial for progressive collapse resistance, the introduction of additional strength and stiffness specifically for progressive collapse can inadvertently create issues. A comparative study [86] using fragility curves demonstrated that design provisions aimed at resisting progressive collapse could lead to a strong-beam-weak-column failure mechanism under seismic loading, a condition that is highly undesirable and would necessitate a costly and

potentially impractical seismic redesign. This finding underscores the necessity for a comprehensive integrated multi-hazard design approach, rather than the sequential application of codes. The optimization framework presented by another study [88], which combined nonlinear dynamic analysis with a global optimization algorithm, offers a promising path forward. By simultaneously considering both seismic and progressive collapse performance criteria, such an integrated approach can identify design solutions that achieve robust performance across multiple hazards without sacrificing efficiency or leading to unintended consequences. This highlights that the most resilient designs are not necessarily those that maximize strength for a single scenario, but those that achieve a balanced combination of strength, ductility, and redundancy tailored to the full spectrum of credible threats a structure may face.

4. Discussion

The synthesis of findings from this systematic review reveals a field that has matured significantly over the past two decades, yet several critical disconnects persist between advanced research capabilities and practical design implementation. Taken together, the evidence from computational, experimental, and probabilistic studies converges on a central insight: the progressive collapse resistance of reinforced concrete structures is fundamentally a system-level property governed by the structure's ability to mobilize large-deformation mechanisms, and this ability is profoundly influenced by the nature of the initiating event. This synthesis moves beyond simply cataloging individual results to reveal a coherent narrative about how our understanding has evolved and where the most pressing knowledge gaps remain. A pattern that emerges consistently across the reviewed studies is the critical role of tensile membrane action in slabs and catenary action in beams as the ultimate defense against collapse. Experimental investigations on beam-column sub-assemblages [146] [153] have unequivocally demonstrated that the transition from flexural or compressive arch action to catenary action occurs at deformations of approximately one beam depth, and that the maximum capacity

from catenary action is typically reached at deflections of about ten percent of the beam span. This large-deformation regime, however, is precisely where many conventional design assumptions break down. The finding that a non-seismically designed beam-column sub-assemblage fails by concrete crushing at the exterior joint before catenary action can even begin [36] underscores a fundamental vulnerability in code-compliant structures that lack adequate ductility. Conversely, seismically detailed specimens consistently demonstrate the ability to sustain these large rotations and engage catenary tension, a finding corroborated across multiple experimental programs [74] [148]. The implication is clear: the rotational ductility provisions inherent in modern seismic design codes, particularly those related to joint confinement and transverse reinforcement spacing, constitute a de facto and highly effective progressive collapse mitigation strategy. However, this conclusion must be tempered by the observation that seismic detailing alone is not universally sufficient, particularly in structures where the initiating event is not an idealized column removal but a realistic impact scenario.

The most profound contradiction exposed by this review lies between the conventional alternate path method prescribed by design guidelines and the more realistic impact-induced column removal (ICR) scenario. The body of numerical research on ICR [143] [144] reveals that the impact of a vehicle or falling debris on a column generates a distinct downward pulling force that acts in concert with gravity, accelerating the downward movement of the column's removal point and placing significantly greater demand on the remaining structure than does instantaneous column removal. This downward force fundamentally changes the dynamics of load redistribution, as it alters the transition from flexural to catenary action by imposing an initial velocity and additional kinetic energy on the structure. The acceleration of the column removal point, a metric that can be used to quantify this downward force [143], is simply not captured in conventional studies that suddenly release a prestressed support. Furthermore, the energy dissipation mechanisms associated with the impact event

itself, such as the crushing of concrete at the impact zone and the inelastic deformation of the impacting object, are event-dependent and are almost universally neglected in standard progressive collapse assessments [144]. The practical implications of this finding are significant and concerning: current design codes, which are largely predicated on the results of idealized column removal studies, may systematically underestimate the collapse potential for structures exposed to credible impact threats. There is a pressing need for design provisions to explicitly consider the impulsive nature of impact loading, perhaps through the introduction of an additional dynamic load factor or through more stringent requirements for the development of catenary action in perimeter beams that are more likely to be struck.

The implications of our synthesis for practitioners and code developers are substantial. From a practical standpoint, the consistent finding that floor slabs contribute between one-third and one-half of the total collapse resistance in beam-slab systems [69] [79] [106] [150] mandates that slabs must be explicitly modeled in any progressive collapse analysis intended for design verification. Ignoring the slab, as is often done in simplified two-dimensional frame analyses, not only underestimates the overall capacity but also misrepresents the load path, as the slab's compressive and tensile membrane actions fundamentally alter the stress distribution in the supporting beams. For practitioners, this implies that three-dimensional models incorporating shell elements for slabs, even if simplified, are essential for a reliable assessment. Regarding enhancement strategies, our synthesis suggests that designers should prioritize approaches that improve rotational ductility and enable the formation of tensile load paths, rather than solely focusing on increasing flexural strength. Externally bonded FRP [24] [43], mid-depth reinforcement [19] [149], and external steel plates [26] all operate on this principle by enhancing the structure's ability to deform without losing its load-carrying capacity. For code developers, the implications extend to the definition of acceptable performance. The current code-based reliance on a dynamic

amplification factor (DAF) of 2.0, as used in linear static procedures, has been shown to be conservative in some contexts [98] [132] but potentially unconservative in others, particularly for structures undergoing significant inelastic deformation and catenary action [58]. The evidence from dynamic tests [130] suggests that the DAF for forces in well-detailed structures undergoing catenary action is often lower than 2.0, but this should not be interpreted as justification for simplifying the analysis procedure. Instead, the most reliable path forward is to require nonlinear dynamic analysis for all but the simplest structures, as this approach consistently provides the closest match to experimental data [41].

Several methodological limitations inherent in this systematic review must be acknowledged, as they likely influence the robustness and generalizability of our conclusions. First, the restriction of our search to English-language publications represents a significant potential source of bias. Countries such as China, Japan, and those in Eastern Europe have vibrant structural engineering research communities and have contributed substantially to the field of progressive collapse, yet important work published in local languages may have been excluded. The impact of this language bias is difficult to quantify, but it is plausible that it could skew our synthesis toward findings that are more common in English-language journals, which may have different editorial priorities regarding novelty and scale of study. Second, the requirement that included studies be peer-reviewed, while ensuring a baseline of quality, likely introduces a publication bias against negative results or studies that fail to show a clear improvement in collapse resistance from a proposed mitigation strategy. The literature is overwhelmingly populated by studies demonstrating the success of various enhancement techniques, which may paint an overly optimistic picture of the current state of mitigation effectiveness. Third, the inherent subjectivity in the quality assessment of computational studies is a limitation. While we have synthesized findings based on the reported validation against experimental data, the rigor of this validation varies considerably across studies. Some investigations use a single experimental

test for calibration, while others employ a more robust multi-case validation. This heterogeneity in the evidence base means that some of the quantitative findings we report, such as specific percentages of load resistance contributed by slabs or reductions in displacement from FRP, should be interpreted as indicative ranges rather than precise benchmarks. Finally, the reliance on keyword-based search strategies may have inadvertently excluded studies that use synonymous but less common terminology, such as "disproportionate collapse" instead of "progressive collapse," potentially omitting relevant European research.

Based on the gaps and inconsistencies identified in this review, several promising directions for future research emerge. There is an urgent need for comprehensive experimental validation of impact-induced column removal scenarios at realistic scales. While numerical simulations have convincingly demonstrated the adverse effects of the downward pulling force, controlled laboratory tests that subject columns to controlled impacts and then assess the subsequent collapse resistance of the frame would provide the data necessary to calibrate and validate the specialized numerical models used in these studies. Future research should explore the development of a standardized impact test procedure that could be incorporated into future code development.

Another understudied area is the optimization of structural design for multi-hazard environments. The finding that progressive collapse mitigation can inadvertently compromise seismic performance [86] highlights a critical lack of integrated design frameworks. There is a need for research that develops and validates performance-based design methodologies which simultaneously satisfy seismic and progressive collapse performance objectives. Such research should leverage the optimization frameworks that have already been proposed [88], extending them to consider multiple hazard scenarios with different probabilities of occurrence and consequence severities. This would allow for the identification of design solutions that achieve robust performance across the hazard spectrum without the sequential application of codes that

can lead to material waste and unintended weak-story mechanisms.

Furthermore, the role of non-structural elements, particularly masonry infill walls, in progressive collapse resistance remains incompletely understood and insufficiently integrated into design practice. While several studies have shown that infill walls significantly improve initial stiffness and peak resistance [83] [151] [153], their contribution is typically neglected in design because they are considered non-structural and their presence is not guaranteed over the life of a building. Future research should explore probabilistic frameworks that account for the probability that infill walls are present and intact at the time of a collapse-triggering event, allowing for a more realistic assessment of system-level robustness. The development of simple, reliable macromodels that can capture the essential truss action of infill walls for use in system-level analyses is a related technical need.

There is a pressing need to extend probabilistic and reliability-based assessment frameworks from the research domain into practical design tools. The studies reviewed here that employ fragility analysis [32] [33] [123] and reliability assessment [55] [156] clearly demonstrate that considering uncertainties in material properties, loading, and modeling parameters can dramatically change the assessment of collapse risk. The failure probability of a frame may increase by more than thirty percent after accounting for realistic uncertainties [87]. Future research should focus on developing computationally efficient surrogate models, perhaps based on machine learning or polynomial chaos expansion [156], that can be integrated into performance-based design software to allow engineers to perform probabilistic progressive collapse assessments as part of routine practice. This would transform the field from one that is primarily reactive, analyzing specific hazards after they occur, to one that is proactive, designing for a quantifiable level of robustness against a spectrum of uncertain threats.

5. Conclusion

This systematic review critically synthesized the state-of-the-art in nonlinear dynamic analysis of

reinforced concrete structures under progressive collapse, focusing on computational modeling, impact loading mechanisms, and robustness enhancement strategies. Our analysis confirms that the field has evolved from simplified static assessments toward sophisticated numerical frameworks, yet a fundamental disconnect persists between advanced research and practical code provisions. The primary contribution of this synthesis is the explicit demonstration that the nature of the initiating event—particularly impact-induced column removal—introduces a downward pulling force that conventional idealized column removal scenarios fail to capture, thereby systematically underestimating structural demand. Furthermore, we have established that the effectiveness of any robustness enhancement strategy is contingent upon its capacity to promote large-deformation mechanisms such as catenary action in beams and tensile membrane action in slabs rather than merely increasing flexural strength.

The practical implications of these findings are substantial for both designers and code developers. Current design guidelines, which rely heavily on the alternate path method with instantaneous column removal, may provide an unconservative assessment of collapse risk for structures exposed to credible impact threats. We recommend that future code revisions explicitly incorporate impact-induced dynamic forces and mandate nonlinear dynamic analysis as the standard procedure for all but the simplest structures. From a design standpoint, prioritizing rotational ductility through seismic detailing, the inclusion of additional mid-depth reinforcement, or the application of externally bonded FRP offers the most reliable pathway to enhanced robustness. Future research should focus on multi-hazard optimization frameworks that reconcile progressive collapse resistance with seismic performance, and on the development of computationally efficient probabilistic tools that enable routine uncertainty quantification in design practice. The road ahead lies in bridging the gap between research fidelity and practical applicability, ensuring that the sophisticated understanding we have gained translates into safer, more resilient infrastructure.

References

- M Byfield, W Mudalige, C Morison, et al. (2014) A review of progressive collapse research and regulations. In *Proceedings of the Institution of Civil Engineers - Structures and Buildings*.
- OA Mohamed (2006) Progressive collapse of structures: annotated bibliography and comparison of codes and standards. *Journal of performance of constructed facilities*.
- K Fujikake, B Li & S Soeun (2009) Impact response of reinforced concrete beam and its analytical evaluation. *Journal of structural engineering*.
- J Jiang (1994) Nonlinear finite element analysis of reinforced concrete structures. Shaanxi Science and Technology Press, Xi'an, China ..., 1994.
- S Amiri, H Saffari & J Mashhadi (2018) Assessment of dynamic increase factor for progressive collapse analysis of RC structures. *Engineering Failure Analysis*.
- K Meguro & H Tagel-Din (2000) Applied element method for structural analysis theory and application for linear materials. *Doboku Gakkai Ronbunshu*.
- Y Bao, SK Kunnath, S El-Tawil, et al. (2008) Macromodel-based simulation of progressive collapse: RC frame structures. *Journal of Structural Engineering*.
- P Ruth, KA Marchand & EB Williamson (2006) Static equivalency in progressive collapse alternate path analysis: Reducing conservatism while retaining structural integrity. *Journal of Performance of Constructed Facilities*.
- AT Pham & KH Tan (2017) Experimental study on dynamic responses of reinforced concrete frames under sudden column removal applying concentrated loading. *Engineering Structures*.
- IMH Alshaikh, AA Abadel & M Alrubaidi (2022) Precast RC structures' progressive collapse resistance: Current knowledge and future requirements. *Structures*.
- MJ Page, JE McKenzie, PM Bossuyt, et al. (2021) The PRISMA 2020 statement: An

- updated guideline for reporting systematic reviews. *BMJ*, 372:n71.
- J. Adam, M. Buitrago, E. Bertolesi, J. Sagaseta & J. Moragues (2020) Dynamic performance of a real-scale reinforced concrete building test under a corner-column failure scenario. *Engineering Structures*.
- ZA Al-Sadoon, MT Junaid, U Al-Sabouni, et al. (2024) Resilience of code compliant reinforced concrete buildings to progressive collapse: A numerical analysis investigation. *Results in Engineering*.
- YA Al-Salloum, TH Almusallam, et al. (2015) Progressive collapse analysis of RC buildings against internal blast. *Advances in Structural Engineering*.
- Y. Al-Salloum, H. Abbas, T. Almusallam, T. Ngo & P. Mendis (2017) Progressive collapse analysis of a typical RC high-rise tower. *Journal of King Saud University: Engineering Sciences*, 29:313-320.
- M. Alanani, M. Ehab & H. Salem (2020) Progressive collapse assessment of precast prestressed reinforced concrete beams using applied element method. *Case Studies in Construction Materials*, 13.
- TH Almusallam, HM Elsanadedy, H Abbas, et al. (2010) Numerical analysis for progressive collapse potential of a typical framed concrete building. *International Journal of Civil and Environmental Engineering*.
- TH Almusallam, HM Elsanadedy, et al. (2010) Progressive collapse analysis of a RC building subjected to blast loads. *Structural Engineering and Mechanics*.
- K Alogla, L Weekes & L Augustus-Nelson (2016) A new mitigation scheme to resist progressive collapse of RC structures. *Construction and Building Materials*.
- Kamal Alogla, L. Weekes & Levingshan Augustus-Nelson (2016) Progressive collapse resisting mechanisms of reinforced concrete structures.
- TMS Alrudaini (2011) A new mitigation scheme to resist the progressive collapse of reinforced concrete buildings. *University of Wollongong, School of Civil, Mining and Environmental Engineering*.
- IMH Alshaikh, BHA Bakar, EAH Alwesabi, AM Zeyad, et al. (2021) Finite element analysis and experimental validation of progressive collapse of reinforced rubberized concrete frame. *Structures*.
- Ibrahim M. H. Alshaikh, A. Abadel, K. Sennah, M. Nehdi, R. Tuladhar & M. Alamri (2022) Progressive Collapse Resistance of RC Beam-Slab Substructures Made with Rubberized Concrete. *Buildings*.
- Ibrahim M.H. Alshaikh, Moncef L. Nehdi & Aref A. Abadel (2024) Numerical investigations on progressive collapse of rubberized concrete frames strengthened by CFRP sheets. *Structures*, 60:105918.
- A. Altheeb, Ibrahim M. H. Alshaikh, A. Abadel, M. Nehdi & Hussam Alghamdi (2022) Effects of Non-Structural Walls on Mitigating the Risk of Progressive Collapse of RC Structures. *Latin American Journal of Solids and Structures*.
- AH Arshian & G Morgenthal (2017) Three-dimensional progressive collapse analysis of reinforced concrete frame structures subjected to sequential column removal. *Engineering Structures*.
- AH Arshian, G Morgenthal & S Narayanan (2016) Influence of modelling strategies on uncertainty propagation in the alternate path mechanism of reinforced concrete framed structures. *Engineering Structures*.
- Y Bao & SK Kunnath (2010) Simplified progressive collapse simulation of RC frame-wall structures. *Engineering Structures*.
- V De Biagi, F Parisi, D Asprone, B Chiaia, et al. (2017) Collapse resistance assessment through the implementation of progressive damage in finite element codes. *Engineering Structures*.
- L. Bredean & M. Botez (2018) The influence of beams design and the slabs effect on the progressive collapse resisting mechanisms development for RC framed structures. *Engineering Failure Analysis*.

- E Brunesi & R Nascimbene (2014) Extreme response of reinforced concrete buildings through fiber force-based finite element analysis. *Engineering Structures*.
- E Brunesi & F Parisi (2017) Progressive collapse fragility models of European reinforced concrete framed buildings based on pushdown analysis. *Engineering Structures*.
- E Brunesi, R Nascimbene, F Parisi & N Augenti (2015) Progressive collapse fragility of reinforced concrete framed structures through incremental dynamic analysis. *Engineering Structures*.
- G Campione (2021) Effect of progressive collapse of central column on the push-down response of two-span beam-column substructures. *Engineering Structures*.
- Yi Cheng, Jun Liu, Lei Sun, Zhimin Xiao & Chen Ou (2023) Dynamic Performance of Multi-Column Removal Framed Structures Subjected to Impact and Heaped Loads. *Structural Engineering International*, 34:657 - 669.
- H Choi & J Kim (2011) Progressive collapse-resisting capacity of RC beam-column sub-assembly. *Magazine of concrete research*.
- L Chu, G Li, D Li & J Zhao (2017) Study on Progressive Collapse Behavior of SRC Column-Steel Beam Hybrid Frame Based on Pushdown Analysis. *Shock and Vibration*.
- PX Dat & TK Hai (2013) Membrane actions of RC slabs in mitigating progressive collapse of building structures. *Engineering Structures*.
- PX Dat, TK Hai & Y Jun (2015) A simplified approach to assess progressive collapse resistance of reinforced concrete framed structures. *Engineering Structures*.
- M. Diao, Yi Li, H. Guan, Xinzheng Lu & B. Gilbert (2020) Influence of horizontal restraints on the behaviour of vertical disproportionate collapse of RC moment frames. *Engineering Failure Analysis*.
- A. Dmitriev & V. Lalin (2021) Comparison of Different Procedures for Progressive Collapse Analysis of RC Flat Slab Structures under Corner Column Loss Scenario. *Buildings*.
- Tin V. Do, T. Pham & H. Hao (2019) Impact force profile and failure classification of reinforced concrete bridge columns against vehicle impact. *Engineering Structures*.
- M. Ebadi-Jamkhaneh, D. Kontoni & Amir Homaioon Ebrahimi (2024) Assessment of Different Methods for Enhancing Progressive Collapse Resistance of Irregular Reinforced Concrete Buildings Using Pushdown Analysis. *Arabian Journal for Science and Engineering*, 49:13861 - 13883.
- Mohammed El-desoqi, M. Ehab & H. Salem (2020) Progressive collapse assessment of precast reinforced concrete beams using applied element method. *Case Studies in Construction Materials*.
- S Elkoly & B El-Ariss (2014) Progressive collapse evaluation of externally mitigated reinforced concrete beams. *Engineering Failure Analysis*.
- HM Elsanadedy, YA Al-Salloum, TH Almusallam, et al. (2019) Assessment of progressive collapse potential of special moment resisting RC frames- Experimental and FE study. *Engineering Failure ...*
- H. Elsanadedy, Y. Al-Salloum, Mohammed Alrubaidi, T. Almusallam & H. Abbas (2020) Finite element analysis for progressive collapse potential of precast concrete beam-to-column connections strengthened with steel plates. *Journal of building engineering*.
- J Esfandiari & MK Latifi (2019) Numerical study of progressive collapse in reinforced concrete frames with FRP under column removal. *Advances in concrete construction*.
- CT Fallon, SE Quiel & CJ Naito (2016) Uniform pushdown approach for quantifying building-frame robustness and the consequence of disproportionate collapse. *Journal of Performance of Constructed Facilities*.
- C. Fang & D. Linzell (2021) Examining progressive collapse robustness of a

- high-rise reinforced concrete building. *Engineering Structures*.
- A Fascetti, SK Kunnath & N Nisticò (2015) Robustness evaluation of RC frame buildings to progressive collapse. *Engineering Structures*.
- D. Feng, Gang Wu & Yong Lu (2018) Numerical Investigation on the Progressive Collapse Behavior of Precast Reinforced Concrete Frame Subassemblages. *Journal of Performance of Constructed Facilities*.
- D. Feng, Zhun Wang & Gang Wu (2019) Progressive collapse performance analysis of precast reinforced concrete structures. *The Structural Design of Tall and Special Buildings*, 28.
- D. Feng, Si-Cong Xie, C. Ning & Shi-Xue Liang (2019) Investigation of Modeling Strategies for Progressive Collapse Analysis of RC Frame Structures. *Journal of Performance of Constructed Facilities*, 33:04019063.
- D. Feng, Si-Cong Xie, Jun Xu & Kai Qian (2020) Robustness quantification of reinforced concrete structures subjected to progressive collapse via the probability density evolution method. *Engineering Structures*, 202:109877.
- DC Feng, HR Shi, F Parisi, E Brunesi, et al. (2021) Efficient numerical model for progressive collapse analysis of prestressed concrete frame structures. *Engineering Failure Analysis*.
- DC Feng, MX Zhang, E Brunesi, F Parisi, J Yu, et al. (2022) Investigation of 3D effects on dynamic progressive collapse resistance of RC structures considering slabs and infill walls. *Journal of Building Engineering*.
- Massimiliano Ferraioli, Biagio Laurenza, Angelo Lavino & Gianfranco De Matteis (2023) Progressive collapse analysis and retrofit of a steel-RC building considering catenary effect. *Journal of Constructional Steel Research*, 213:108364.
- F Fu (2009) Progressive collapse analysis of high-rise building with 3-D finite element modeling method. *Journal of constructional steel research*.
- Y Gan, J Chen & M Xiang (2023) PDEM-based reliability assessment of RC frames against progressive collapse considering initial local failure. *Journal of Building Engineering*.
- S Gowtham, M Prakash, N Parthasarathi, et al. (2018) 2D-Linear static and non-linear dynamic progressive collapse analysis of reinforced concrete building. In *Materials Today: Proceedings*.
- C Grunwald, AA Khalil, B Schaufelberger, et al. (2018) Reliability of collapse simulation-Comparing finite and applied element method at different levels. *Engineering Structures*.
- XL Gu, B Zhang, Y Wang & XL Wang (2021) Experimental investigation and numerical simulation on progressive collapse resistance of RC frame structures considering beam flange effects. *Journal of Building Engineering*.
- I Hafez, A Khalil & S Mourad (2013) Alternate path method analysis of RC structures using applied element method. *International Journal of Protective Structures*.
- Xiao-Huang-Can He, W. Yi & Xian-Xun Yuan (2019) A non-iterative progressive collapse design method for RC structures based on virtual thermal pushdown analysis. *Engineering Structures*.
- H Helmy, H Salem & S Mourad (2012) Progressive collapse assessment of framed reinforced concrete structures according to UFC guidelines for alternative path method. *Engineering Structures*.
- J. Hou & Li Song (2016) Progressive Collapse Resistance of RC Frames under a Side Column Removal Scenario: The Mechanism Explained. *International Journal of Concrete Structures and Materials*, 10:237 - 247.
- H Huang, M Huang, W Zhang, M Guo, Z Chen, et al. (2021) Progressive collapse resistance of multistory RC frame strengthened with HPFL-BSP. *Journal of Building Engineering*.
- H Huang, M Huang, W Zhang, M Guo, et al. (2022) Progressive collapse of multistory

- 3D reinforced concrete frame structures after the loss of an edge column. *Structure and Infrastructure Engineering*.
- BS Iribarren, P Berke, P Bouillard, J Vantomme, et al. (2011) Investigation of the influence of design and material parameters in the progressive collapse analysis of RC structures. *Engineering Structures*.
- I Tabaeye Izadi & A Ranjbaran (2012) Investigation on a mitigation scheme to resist the progressive collapse of reinforced concrete buildings. *Frontiers of Structural and Civil Engineering*.
- SJ Ju & HG Kwak (2023) Analytical model for progressive collapse of RC frame structures subjected to blast loadings. *Journal of Building Engineering*.
- G Kaewkulchai & EB Williamson (2004) Beam element formulation and solution procedure for dynamic progressive collapse analysis. *Computers & Structures*.
- Q Kai & B Li (2012) Dynamic performance of RC beam-column substructures under the scenario of the loss of a corner column—Experimental results. *Engineering Structures*.
- Seyed Ali Ekrami Kakhki, A. Kheyroddin & A. Mortezaei (2023) Numerical Investigation of the Progressive Collapse of the Reinforced Concrete Wall-Frame Structures Considering the Soil-Structure Interaction. *International Journal of Concrete Structures and Materials*, 17:1-24.
- HS Kim & HH Wee (2016) Separation strain for progressive collapse analysis of reinforced concrete building using applied element method. *Advances in Structural Engineering*.
- S Kokot (2022) Response spectrum of a reinforced concrete frame structure under various column removal scenarios. *Journal of Building Engineering*.
- DQ Lan, L Jin, K Qian, RB Zhang & J Li (2023) Progressive collapse resistance of RC frames subjected to localized fire. *Journal of Building Engineering*.
- A Laskar, H Gu, YL Mo & G Song (2009) Progressive collapse of a two-story reinforced concrete frame with embedded smart aggregates. *Smart Materials and Structures*.
- JL Le & B Xue (2014) Probabilistic analysis of reinforced concrete frame structures against progressive collapse. *Engineering Structures*.
- H.S. Lew, Yihai Bao, Fahim Sadek, Joseph A. Main, Santiago Pujol & Mete A. Sozen (2011) An Experimental and Computational Study of Reinforced Concrete Assemblies under a Column Removal Scenario. National Institute of Standards and Technology.
- J Li & H Hao (2013) Numerical study of structural progressive collapse using substructure technique. *Engineering Structures*.
- S Li, S Shan, C Zhai & L Xie (2016) Experimental and numerical study on progressive collapse process of RC frames with full-height infill walls. *Engineering Failure Analysis*.
- Zhongxian Li, Bo Zhong, Yanchao Shi, Yang Ding & Y. Hao (2019) A computationally efficient numerical model for progressive collapse analysis of reinforced concrete structures. *International Journal of Protective Structures*, 10:330 - 358.
- R Li, J Yu, X Zhou & M Zhao (2023) Analysis of progressive collapse process of RC structures based on hybrid framework of FEM-physics engine. *Engineering Failure Analysis*.
- K Lin, Y Li, X Lu & H Guan (2017) Effects of seismic and progressive collapse designs on the vulnerability of RC frame structures. *Journal of Performance of Constructed Facilities*.
- K Lin, Z Chen, Y Li & X Lu (2022) Uncertainty analysis on progressive collapse of RC frame structures under dynamic column removal scenarios. *Journal of Building Engineering*.
- K Lin, Z Wu, Y Zhu, J Zheng, Y Li & X Lu (2023) Progressive collapse design optimization of RC frame structures using high-performance computing. *Structures*.
- X Long, PM Iyela, Y Su, MM Atlaw & SB Kang (2024) Numerical predictions of

- progressive collapse in reinforced concrete beam-column sub-assemblages: A focus on 3D multiscale modeling. *Engineering Structures*.
- X Lu, X Lin & L Ye (2009) Simulation of structural collapse with coupled finite element-discrete element method. In *International Symposium on Computational Structural Engineering*.
- DG Lu, SS Cui, PY Song, et al. (2012) Robustness assessment for progressive collapse of framed structures using pushdown analysis methods. *International Journal of Reliability and Safety*.
- X Lu, Y Li, H Guan & M Ying (2017) Progressive collapse analysis of a typical super-tall reinforced concrete frame-core tube building exposed to extreme fires. *Fire technology*.
- Xinzheng Lu, Kaiqi Lin, Yi Li, H. Guan, Peiqi Ren & Yu-long Zhou (2017) Experimental investigation of RC beam-slab substructures against progressive collapse subject to an edge-column-removal scenario. *Engineering Structures*, 149:91-103.
- A McKay, K Marchand & M Diaz (2012) Alternate path method in progressive collapse analysis: Variation of dynamic and nonlinear load increase factors. *Practice Periodical on Structural Design and Construction*.
- K Menchel, TJ Massart, Y Rammer, et al. (2009) Comparison and study of different progressive collapse simulation techniques for RC structures. *Journal of Structural Engineering*.
- KM Mosalam, M Talaat & S Park (2008) Modeling progressive collapse in reinforced concrete framed structures. In *Proceedings of the 14th World Conference on Earthquake Engineering*.
- G. Mucedero, E. Brunesi & F. Parisi (2020) Nonlinear material modelling for fibre-based progressive collapse analysis of RC framed buildings. *Engineering Failure Analysis*, 118:104901.
- S. Nyunn, Feiliang Wang, Jian Yang, Qing-feng Liu, I. Azim & Sanjeev Bhatta (2020) Numerical studies on the progressive collapse resistance of multi-story RC buildings with and without exterior masonry walls. *Structures*, 28:1050-1059.
- SL Orton & JE Kirby (2014) Dynamic response of a RC frame under column removal. *Journal of Performance of Constructed Facilities*.
- S. Panahi & S. M. Zahrai (2021) Performance of typical plan concrete buildings under progressive collapse. *Structures*, 31:1163-1172.
- F. Petrone, L. Shan & S. Kunnath (2016) Modeling of RC Frame Buildings for Progressive Collapse Analysis. *International Journal of Concrete Structures and Materials*, 10:1-13.
- AT Pham, KH Tan & J Yu (2017) Numerical investigations on static and dynamic responses of reinforced concrete sub-assemblages under progressive collapse. *Engineering Structures*.
- K Qian & B Li (2012) Experimental and analytical assessment on RC interior beam-column subassemblages for progressive collapse. *Journal of performance of constructed facilities*.
- K Qian & B Li (2017) Dynamic and residual behavior of reinforced concrete floors following instantaneous removal of a column. *Engineering Structures*.
- K Qian, B Li & JX Ma (2015) Load-carrying mechanism to resist progressive collapse of RC buildings. *Journal of Structural Engineering*.
- K Qian, B Li & ZW Zhang (2015) Testing and simulation of 3D effects on progressive collapse resistance of RC buildings. *Magazine of Concrete Research*.
- Kai Qian, S. Liang, D. Feng, F. Fu & Gang Wu (2020) Experimental and Numerical Investigation on Progressive Collapse Resistance of Post-Tensioned Precast Concrete Beam-Column Subassemblages. *Journal of Structural Engineering-asce*, 146:04020170.
- Kai Qian, Yun-Hao Weng, F. Fu & Xiao-Fang Deng (2021) Numerical evaluation of the reliability of using single-story substructures to study progressive collapse behaviour of multi-story RC frames. *Journal of Building Engineering*.

- K Qian, XY Chen & T Huang (2022) Dynamic response of RC beam-slab substructures following instantaneous removal of columns. *Journal of Building Engineering*.
- W Qin, Z Zhang, Z Xi & D Wang (2023) Experimental investigation on the progressive collapse resistance of UHPC-RC composite beam-column structures. *Engineering Structures*.
- JG Qin, WW Zhang, T Huang, K Qian & XF Deng (2024) Effect of steel reinforcement corrosion on progressive collapse resistant of beam-slab structure with interior column failure. *Engineering Structures*.
- AM Remennikov & S Kaewunruen (2020) Impact resistance of reinforced concrete columns: experimental studies and design considerations. *Progress in Mechanics of Structures and Materials*.
- P Ren, Y Li, X Lu, H Guan & Y Zhou (2016) Experimental investigation of progressive collapse resistance of one-way reinforced concrete beam-slab substructures under a middle-column-removal scenario. *Engineering Structures*.
- HM Salem, AK El-Fouly & HS Tagel-Din (2011) Toward an economic design of reinforced concrete structures against progressive collapse. *Engineering Structures*.
- M Sasani & J Kropelnicki (2008) Progressive collapse analysis of an RC structure. *The Structural Design of Tall and Special Buildings*.
- M Sasani & S Sagioglu (2008) Progressive collapse resistance of hotel San Diego. *Journal of structural engineering*.
- M Sasani, M Bazan & S Sagioglu (2007) Experimental and analytical progressive collapse evaluation of actual reinforced concrete structure. *ACI Structural Journal*.
- M Sasani, A Kazemi, S Sagioglu, et al. (2011) Progressive collapse resistance of an actual 11-story structure subjected to severe initial damage. *Journal of Structural Engineering*.
- M Sasani, A Werner & A Kazemi (2011) Bar fracture modeling in progressive collapse analysis of reinforced concrete structures. *Engineering Structures*.
- M Sasani (2008) Response of a reinforced concrete infilled-frame structure to removal of two adjacent columns. *Engineering Structures*.
- M. Scalvenzi & F. Parisi (2020) Progressive collapse capacity of a gravity-load designed RC building partially collapsed during structural retrofitting. *Engineering Failure Analysis*.
- M. Scalvenzi, S. Gargiulo, F. Freddi & F. Parisi (2021) Impact of seismic retrofitting on progressive collapse resistance of RC frame structures. *Engineering Failure Analysis*.
- M Scalvenzi, S Ravasini, E Brunesi & F Parisi (2023) Progressive collapse fragility of substandard and earthquake-resistant precast RC buildings. *Engineering Structures*.
- MH Scott & GL Fenves (2010) Krylov subspace accelerated Newton algorithm: application to dynamic progressive collapse simulation of frames. *Journal of structural engineering*.
- Y Su, Y Tian & X Song (2009) Progressive collapse resistance of axially-restrained frame beams. *ACI Structural Journal*.
- M Talaat & KM Mosalam (2009) Modeling progressive collapse in reinforced concrete buildings using direct element removal. *Earthquake Engineering & Structural Dynamics*.
- MM Talaat (2007) Computational modeling of progressive collapse in reinforced concrete frame structures. search.proquest.com.
- KH Tan (2025) Experimental study on progressive collapse behaviour of intact and slightly earthquake-damaged exterior precast concrete joints, and finite element modelling of *Engineering Structures*.
- H. Tavakoli & F. Kiakojoori (2013) Numerical Study of Progressive Collapse in Framed Structures: A New Approach for Dynamic Column Removal. *International Journal of Engineering*, 26:685-692.

- Y Tian & Y Su (2011) Dynamic response of reinforced concrete beams following instantaneous removal of a bearing column. *International Journal of Concrete Structures and Materials*.
- M Tohidi, J Yang & C Baniotopoulos (2014) Numerical evaluations of codified design methods for progressive collapse resistance of precast concrete cross wall structures. *Engineering structures*.
- MH Tsai & BH Lin (2008) Investigation of progressive collapse resistance and inelastic response for an earthquake-resistant RC building subjected to column failure. *Engineering structures*.
- N Usefi, F Mohajeri Nav & R Abbasnia (2016) Finite element analysis of RC elements in progressive collapse scenario. *Gradjevinar*.
- M Vinay, PKR Rao, S Dey, AHL Swaroop, et al. (2022) Evaluation of progressive collapse behavior in reinforced concrete buildings. *Structures*.
- J Weng, KH Tan & CK Lee (2017) Modeling progressive collapse of 2D reinforced concrete frames subject to column removal scenario. *Engineering Structures*.
- Jian Weng, C. Lee, K. Tan & Namyoo Salim Lim (2017) Damage assessment for reinforced concrete frames subject to progressive collapse. *Engineering Structures*, 149:147-160.
- Jian Weng, C. Lee & K. Tan (2020) Simplified Dynamic Assessment for Reinforced-Concrete Structures Subject to Column Removal Scenarios. *Journal of Structural Engineering-asce*, 146:04020278.
- Yun-Hao Weng, Kai Qian, F. Fu & Q. Fang (2020) Numerical investigation on load redistribution capacity of flat slab substructures to resist progressive collapse. *Journal of Building Engineering*.
- Z Xu & Y Huang (2024) Finite element analysis of progressive collapse resistance of precast concrete frame beam-column substructures with UHPC connections. *Journal of Building Engineering*.
- Youwu Xu, Yue Zheng & Q. Gu (2018) Refined dynamic progressive collapse analysis of RC structures. *Bulletin of Earthquake Engineering*, 16:1293-1322.
- B Xue & JL Le (2016) Stochastic computational model for progressive collapse of reinforced concrete buildings. *Journal of Structural Engineering*.
- WJ Yi, QF He, Y Xiao & SK Kunnath (2008) Experimental study on progressive collapse-resistant behavior of reinforced concrete frame structures. *ACI Structural Journal*.
- F. Yi, Wei-jian Yi, Jing-Ming Sun, Jia Ni, Qing-Feng He & Yun Zhou (2024) On the progressive collapse performance of RC frame structures under impact column removal. *Engineering Structures*.
- F Yi, W Yi, H Chen, Y Zhou, L Shen & X Zhang (2026) Progressive collapse of RC frame structures under impact-induced column removal: numerical simulations and energy-based evaluations. *Journal of Building Engineering*.
- J Yu & KH Tan (2013) Experimental and numerical investigation on progressive collapse resistance of reinforced concrete beam column sub-assemblages. *Engineering structures*.
- J Yu & KH Tan (2013) Structural behavior of RC beam-column subassemblages under a middle column removal scenario. *Journal of Structural Engineering*.
- J Yu & KH Tan (2014) Numerical analysis with joint model on RC assemblages subjected to progressive collapse. *Magazine of Concrete Research*.
- J Yu & KH Tan (2014) Special detailing techniques to improve structural resistance against progressive collapse. *Journal of Structural Engineering*.
- J Yu & KH Tan (2022) Component-based joint model for RC frames with conventional and special detailing against progressive collapse. *Structures*.
- J Yu, L Luo & Y Li (2018) Numerical study of progressive collapse resistance of RC beam-slab substructures under perimeter column removal scenarios. *Engineering Structures*.

- Jun Yu, Y. Gan, Jun Wu & Hao Wu (2019) Effect of concrete masonry infill walls on progressive collapse performance of reinforced concrete infilled frames. *Engineering Structures*.
- Jun Yu, Y. Gan & Jun Liu (2020) Numerical study of dynamic responses of reinforced concrete infilled frames subjected to progressive collapse. *Advances in Structural Engineering*, 24:635 - 652.
- J Yu (2012) Structural behavior of reinforced concrete frames subjected to progressive collapse. dr.ntu.edu.sg.
- SM Zahrai & A Ezoddin (2014) Numerical study of progressive collapse in intermediate moment resisting reinforced concrete frame due to column removal. *Civil Engineering Infrastructures Journal*.
- Qiang Zhang, Yan-Gang Zhao, K. Kolozvari & Lei Xu (2020) Simplified model for assessing progressive collapse resistance of reinforced concrete frames under an interior column loss. *Engineering Structures*, 215:110688.
- Q Zhang, YG Zhao, K Kolozvari & L Xu (2022) Reliability analysis of reinforced concrete structure against progressive collapse. *Reliability Engineering and System Safety*.

