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A REVIEW: PROGRESSIVE COLLAPSE ANALYSIS OF RC STRUCTURE

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ABSTRACT

Progressive collapse in reinforced concrete (RC) buildings is one of the most important types of structural failure in which localized damage propagates disproportionately, leading to partial or total structural collapse. This study presents a comprehensive review of progressive collapse behavior in RC systems, with particular emphasis on flat slab–column structures, which are inherently vulnerable due to direct load transfer mechanisms and reduced redundancy. The study shows that punching shear failure at the joints between the block and column is a main cause of collapse, especially when columns are removed. The Alternative Load Path (ALP) method is a well-known way to test how strong a structure is by modelling the quick loss of important parts. Experimental findings indicate that dynamic effects significantly influence structural response, with load amplification reaching up to 124.8% and dynamic amplification factors ranging from 1.09 to 2.6. Key resistance mechanisms, including compressive membrane action, tensile membrane action, and post-punching behavior, are shown to enhance residual load-carrying capacity, with values increasing from approximately 30% to 70% under proper reinforcement detailing.

Numerical simulations using nonlinear finite element methods effectively capture crack propagation, stiffness degradation, and load redistribution, although model accuracy depends on parameter calibration. The study also emphasizes the influence of structural configuration, material degradation, and code provisions such as GSA and DoD guidelines. Overall, enhancing ductility, continuity, and redundancy is essential for improving collapse resistance and ensuring structural safety under extreme loading conditions.

Keywords: Progressive collapse, Reinforced concrete, Flat slab system, Punching shear failure, Load redistribution, Alternative load path, Dynamic analysis, Structural robustness

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I. INTRODUCTION

Progressive Collapse Analysis of RC Buildings is an important area of structural engineering because the reinforced concrete buildings are supposed to stay in place even with the normal gravity and service loads, as well as the infrequent accidental events, which are likely to cause harm to a small portion of the structure [1]. Progressive collapse is a scenario whereby a local failure does not stay confined to a single member, rather it transfers between members and along with it causes a partial or complete collapse several times larger than the initial damage [2].In technical terminology, this implies that the structure will no longer be able to redistribute the load safely once one of its columns, slab areas, or joints is not functional anymore [3]. This may be initiated as a result of fire, gas explosion, impact, corrosion, design failure, construction failure, abnormal overload, or a deliberate attack [4].The problem is more severe in RC buildings since the structural system is very interrelated [5]. The failure of one key member results in immediate redistribution of forces to the other members. Failure can spread through the frame or slab system within a very short period of time unless these adjacent elements have a sufficient reserve strength, ductility, continuity or redundancy [6]. Thus, progressive collapse analysis does not merely focus on the strength of individual members; it focuses on the robustness of the system, alternate load path formation, deformation capacity and the engineering capability to confine the detrimental effects to a small area instead of letting it propagate out of control [7].

The technical significance of this issue has been heightened by the expansion of the modern multistorey and multifunctional building, where the structure design is frequently more complicated and the conditions of loading is more challenging compared to building low-rise constructions [8]. The use of many RC buildings, and more so flat slab-column type, is associated with the idea of providing architectural flexibility, shallowened floor depth, simplified formwork and accelerated construction [9]. These systems have become very popular in parking buildings, apartments and commercial buildings since they directly transfer loads between slabs and columns without deep beam structures [10]. Nevertheless, the vulnerability is also provided by the same structural efficiency. Since the path of load is comparatively short and the redundancy is less than in the conventional beam-supported structures, the slab column joint turns into a hotspot [11]. The uploaded content is very clear about the fact that such joints are highly prone to shear failure by punching, which may serve as a precursor of progressive collapse in beamless RC floor systems. The punching failure of one connection can result in a loss of support over a localised area by the slab and sudden increase of demand by the adjoining spans [12]. a consequence of this, an apparently local punching failure can become a domino effect of other columns, slab panels and floor levels. It is the reason progressive collapse analysis of RC buildings should be particularly concerned with the local joint action, reinforcement continuity, anchorage, and capacity of the floor system to produce alternative mechanisms of resistance following original damage [13].

The failures of historical buildings are a strong sign of why the problem of progressive collapse should be approached both technically and practically [14]. The given material mentions a number of well-known flat-plate and slab-column collapses, which show how local defects or overloads may cause disproportionate collapse. The collapse of a 16 storey cast-in-place flat-plate apartment building in the United States in 1971 was one of the earliest examples. Then, the collapse on the sixteenth floor started at a slab column junction because the roof shoring was removed prematurely resulting in overload of the mechanical room[15] . This issue was exacerbated by poor quality concrete whose compressive strength was not more than 60 percent of the required one. The research found lack of reinforcement development length, inadequate curing methods, and incorrect order of construction as key factors of contribution [16]. The other notable case was the Pipe Row flat-plate parking structure in United Kingdom, which collapsed in 1997, with a punching shear failure happening at a column at the corner where a significant roof slab was placed [17].

There, low design estimation of edge shear, reinforcement corrosion due to carbonation, anchorage degradation, missing comprehensive repair and poor inspection practices were contributing factors [18]. Other examples are Skyline Plaza, Kimberley-Clark warehouse, Morbio shopping complex, and the 2021 Surfside condominium collapse, which were all associated with causes of shore failure, extreme loads being underestimated, freeze-thaw damage, and long-term corrosion [19]. Collectively, these examples demonstrate that progressive collapse cannot be traced to a single design error but rather most often, it is the combination of structural vulnerability, material degradation, the omission of detailing, the lack of maintenance, and the occurrence of abnormal loading conditions [20].

Structural mechanics perspective on progressive collapse analysis of RC buildings is concerned with the behaviour of the building once a critical support or connection has been destroyed or cut [21].In normal design Design In normal design, the members are sized to allow the anticipated combinations of dead load and live load and occasionally wind or earthquake load [22]. However, when it is damaged by accidents, the behavior turns extremely nonlinear and the undamaged structure has to discover new ways of distributing the load [23]. The material uploaded points out 3 significant mechanisms of resistance in flat slab column systems that include tension compression membrane action, joint punching shear mechanism and post-punching shear mechanism [24]. The criticality of these mechanisms is technical due to the fact that they are various phases of structural survival following local damages [25]. Membrane action may occur when the slab experiences great deflection and begins to sustain load using both in-plane forces and not by flexure alone [26]. The joint punching shear resistance is applied to determine the ability of the slab column connection to resist concentrated shear load. The post-punching behavior is essential when local punching already has taken place and yet the structure attempts to resume collapse by means of reinforcement bridging, residual slab and redistributing pressing forces [27]. On In the case of RC buildings in general, other related concepts can be applied even in framed buildings: once columns are lost, beams and slabs should be able to span the lost support, joints should not be destroyed, and reinforcement should be able to hold large tensile strains without brittle anchorage failure. Progressive collapse analysis is therefore closely related to ductility, continuity, confinement, reinforcement detailing, and compatibility of deformation between linked members [28].

Since the phenomenon is associated with the local failure, redistribution of forces within a short time and enormous deformation, it cannot be analyzed using only simple elastic considerations [29].

The issue of progressive collapse in RC buildings is a complicated mechanical challenge, which needs investigation of experimental conduct, theoretical formulation, and numerical simulation [30].

Experimental studies enable engineers to comprehend actual collapse mechanism through observation of slab-column assemblies, beam-column substructures and limited frame systems subjected to observed conditions of damage like removal of columns at the moment [31]. These tests indicate crack propagation, loss of stiffness, redistribution of loads, formation of deflections, yielding of reinforcement, punching and remaining resistance. Theory work is meant to determine the interaction and development of mechanisms of resistance, and to provide simplistic yet rational articulations that can be used to make design recommendations [32].

Nonlinear finite element modeling, in particular, numerical simulation, has been of great value in that it is capable of modeling common since concrete cracking, reinforcement yielding, bond, large displacement, and a varying internal force paths during the process of collapse [33]. The given material observes that despite the research discovering the key mechanisms that oppose collapse in the flat slab system, the interaction between the mechanisms has yet to be completely comprehended and systematic evaluation framework has not been established [34].

This implies that the discipline is moving away out of the analysis of components in isolation, to a comprehensive analysis of robustness [35]. Technically, the progressive collapse analysis should thus not just assess the adequacy of a member, but the ability of the entire RC system to keep operating after some local damage to the system by other means, redistribution capacity, and staged resistance upon extreme deformation [36].

2. RELATED WORK

Sr. No.	Author and Year	Method	Results (values mentioned)	Findings and Outcomes
1	M. Vinay et al. (2022)[37]	Numerical progressive-collapse assessment of RC buildings; comparison of configurations with and without perimeter beams under column-removal scenarios.	Perimeter beams reduced joint displacement and chord rotation at removal locations; assessment used DCR < 2.0 for regular buildings and DCR < 1.5 for irregular buildings.	Perimeter beams significantly improved alternate load-path capacity and structural robustness of RC buildings under progressive-collapse checks. (ScienceDirect)

2	P. Kumar & T. Raghavendra (2022)[38]	Linear static + nonlinear dynamic analysis of G+6, G+8, and G+10 RC frames in ETABS with internal, penultimate, edge, and corner column removal.	Progressive-collapse demand at the bottom end of adjacent columns > 1 in all scenarios; penultimate-column removal was the most critical case.	The study identified penultimate-column loss as more dangerous than many other removal cases and showed that building height influences redistribution severity. (ScienceDirect)
3	I. M. H. Alshaikh et al. (2022)[39]	FE modelling of RC beam–slab substructures under penultimate-column removal; parametric extension with eight additional models.	Slabs contributed more than one-third of the total load resistance.	Slab action is not secondary; it materially strengthens the progressive-collapse resistance of RC systems and should be included in realistic assessment. (MDPI)
4	Z. Zhao et al. (2022)[40]	1 static + 4 dynamic collapse tests on RC beam-column assemblies under a middle-column-removal scenario, plus numerical modelling.	Dynamic response was governed by compressive arch action (CAA) and catenary action (CA); strain-rate effects enhanced resistance in the CA stage, while both dynamic stress redistribution and strain rate increased maximum deformation.	The paper showed why static-only assessment can miss key dynamic effects and supported an energy-based method for estimating dynamic response efficiently. (ScienceDirect)
5	S. A. Ekrami Kakhki et al. (2023)[41]	Nonlinear static pushdown analysis of 20-storey RC wall-frame structures with soil–structure interaction (SSI) using SeismoStruct and FLAC.	Using shear walls reduced the sensitivity index by 5.25%; increasing foundation thickness from 180 to 210 cm increased SI by 6.3%; increasing soil density from 1600 to 2200 kg/m³ reduced SI by 24.7%; changing soil type increased SI by 59%; lowering groundwater level reduced SI by 25%.	SSI, soil density, groundwater, and wall participation strongly affect progressive-collapse vulnerability; neglecting foundation–soil effects can misjudge RC building robustness. (Springer)
6	Q.-L. Fu et al. (2023)[42]	Numerical simulation of multi-storey RC	Frames with 1 to 5 storeys were analysed; increasing the number	Only the first-storey beam developed strong arching and

		frames in DIANA under progressive-collapse scenarios.	of storeys increased both compressive arch action and catenary action capacities.	catenary action in multi-storey systems; upper-storey contribution was mainly flexural, which is important for design modelling. (MDPI)
7	Z. Yang et al. (2023)[43]	Experimental study on a 1/3-scale, 2×2-bay RC flat-plate substructure under slab overloading and joint punching failure.	The specimen was loaded until complete damage after initial punching shear failure at the interior slab-column joint.	The study highlighted that progressive collapse in flat slabs can begin from joint punching, not only from notional column removal, expanding the failure perspective for RC flat-slab buildings. (ScienceDirect)
8	H. Mirzahosseini et al. (2023)[44]	3D OpenSees modelling of five 3-storey RC moment-resisting frames with ordinary joints and HPFRCC joints under corner-column removal.	Five buildings were compared; HPFRCC joints improved stiffness and load capacity, while severe reinforcement reduction in H3 still caused severe connection damage.	HPFRCC in beam-column joints reduced progressive-collapse damage and improved deformation tolerance, but material enhancement cannot fully compensate for excessive reinforcement reduction. (ScienceDirect)
9	J.-F. Cheng et al. (2024)[45]	High-fidelity LS-DYNA modelling of RC frames under corner-column removal; quasi-static vs dynamic comparison.	The study quantified effects of strain rate, damping ratio, slab thickness, and upper-storey constraints; damping markedly reduced peak displacement and vibration amplitude, while strain-rate effects were negligible.	Dynamic behaviour under corner-column loss depends strongly on damping and slab participation; the energy-based method can estimate dynamic resistance without explicitly modelling all rate effects. (ScienceDirect)
10	S. A. Derseh et al. (2024)[46]	GSA-based linear-static progressive-collapse study on eight-storey typical and atypical RC	For first-storey column removal, ATYP_FRM3 reached DCR values of 2.66, 3.79, 3.60, and 8.87 for C1, C2, C3, and C4 removal, respectively;	Atypical framing can either improve or worsen robustness depending on geometry; some irregular layouts substantially

		framed buildings under four column-removal cases.	displacement values included 20 mm, 7.05 mm, −21.86 mm, −24.27 mm, 30 mm, and −73.23 mm depending on frame type and removed column.	amplified DCR and displacement demand. (Springer)
11	V. I. Kolchunov et al. (2024)[47]	Semi-analytical + experimental validation of a precast RC frame system with layered beams for accidental-action resistance.	The proposed model captured shear deformation, longitudinal crack opening, and normal cracking in the layered contact zone; comparison with test data showed satisfactory agreement.	The study proposed a precast RC frame concept aimed at better robustness under accidental actions, but also found that the tested layered-beam system was not fully robust under the specified loading and reinforcement conditions. (MDPI)
12	M. Jadallah et al. (2025)[48]	Applied Element Method (ELS) analysis of 9-, 12-, and 15-storey RC buildings with solid vs ribbed slabs and beam depths of 500, 600, and 700 mm under multiple-column-loss scenarios.	Validation on a real damaged building showed field displacement of about 130 mm, while the model predicted 120–132 mm; ribbed slabs remained stable even with the smallest beam depth, whereas solid slabs needed ≥700 mm beam depth to prevent collapse.	Slab type and beam depth strongly govern robustness; ribbed slabs improved catenary/tensile-membrane action and reduced displacement and plastic rotation. (ScienceDirect)
13	M. Prakash et al. (2025)[49]	Experimental investigation of two-bay, five-storey asymmetrical RC frames under corner-column removal, comparing bare and infilled frames.	Bare frame: elastic up to 2 tons at 0.44 mm displacement; maximum horizontal displacement 8 mm at 16 tons; fifth-storey vertical displacement rose from 4 mm to 7 mm. Infilled frame: elastic up to 2 tons at 0.3 mm; maximum horizontal displacement 3 mm at 8 tons; fifth-storey vertical displacement rose from 2 mm to 3 mm.	Infill walls substantially improved progressive-collapse resistance and reduced both horizontal and vertical displacement after corner-column loss. (ScienceDirect)

14	L. Ding et al. (2025)[50]	System-level study on deteriorated multi-storey RC frames with simulated reinforcement corrosion; static and dynamic alternate-load-path analysis.	Progressive-collapse resistance reduced significantly with increasing corrosion; dynamic resistance was lower than static resistance and decreased faster as corrosion progressed. The critical deterioration was corrosion in beams directly above the removed column.	Existing RC buildings with localized corrosion in directly affected bays may be much more vulnerable than new buildings; corrosion location matters more than uniform deterioration assumptions. (MDPI)
15	J.-L. Wang et al. (2025)[51]	ANSYS/LS-DYNA study of pure and infilled RC spatial frames with different opening layouts under instantaneous column removal.	A complete column-removal device produced 238.1% higher residual displacement than an incomplete device; stiffness dropped by 68.8%.	Infill walls can improve resistance, but opening location and the realism of the column-removal simulation strongly influence the assessed collapse risk. Mid-span openings reduced stiffness more severely. (MDPI)

3. EXPERIMENTAL STUDY ON PROGRESSIVE COLLAPSE OF FLAT SLAB COLUMN STRUCTURE

Progressive Collapse Analysis of RC Buildings is aimed at considering the capacity of the reinforced concrete structures to tolerate local damages due to unanticipated incidents without resulting to disproportionate collapse [52]. In the slab column structures, this is more pronounced because of the lack of beams and direct slab to column load transfer [53]. Experimental work is crucial in learning the behavior of such systems in an abnormal situation particularly when one of the main load bearing structures like a column is abruptly taken away [54]. Designing to withstand progressive collapses demands a clear comprehension of the accidental loading locations but in the real-life circumstances, it is impossible to foretell the exact type, location and scale of such incidents. To guarantee the structural safety and strength, engineers use systematic and generalized methods as opposed to event-specific analysis because of this uncertainty [55].

The Alternative Load Path (ALP) approach is one of the well-known techniques of carrying out experimental and analytical research [56]. In this technique, the performance of the structure is determined by the hypothetical removal of the load Bearing members that are considered to be important without regard to the precise failure mode [57]. The ALP process can be described as comprising three key phases, namely, the process of eliminating the chosen structural elements, testing the load-carrying capacity of the new system, and determining the capability of the structure to redistribute the loads and withstand further collapse. This technique assists in determining the redundancy, continuity and deformation in the structure system. The use of ALP is suggested by international design standards like GSA (2016), UFC 4-023-03 (2016) and Eurocode EN 1993-1-8 (2006), particularly when it comes to significant and high-risk structures [58]. On the structure, these codes also describe increased robustness criteria of critical structures to ensure the structure can withstand the loss of columns in a progressive collapse setting, thus improving inherent structural safety and structural resiliency.

3.1. Types of Experimental Methods

On the background of Progressive Collapse Analysis of RC Buildings, the experimental approaches are important to comprehend the behavior of structures that experience the immediate loss of one of the critical elements of the load [59]. These experimental strategies are broadly divided under two general The quasi-static testing is done at the gradual loading of the structure to represent the pull-out of a structural element, like a column. The technique assists in researching load redistribution mechanisms, deformation capability, cracking behaviour and the formation of the alternative load paths within the reinforced concrete systems particularly the flat slab-column structures [60]. It offers environmental control conditions to measure structural soundness and post failure strength [61]. Dynamic testing, on the other hand, simulates a sudden event like an explosion or impact of a structure by immediately removing a structural element, thus, simulating the effect of inertia, dynamic amplification, and rapid redistribution of loads [62]. This approach is more realistic and difficult and expensive. Collectively, these experimental methods can assist the engineers to identify the mechanisms behind collapse, confirm the numerical models, and enhance the design solutions to ensure that RC building can sustain progressive collapse and retain its structural integrity when exposed to abnormal conditions [63].

3.1.1. Quasi-Static Testing

Generally, progressive collapse assessment through quasi-static testing procedures are conducted in three major steps [64]. First, preferable column elements are deliberately eliminated to establish an abrupt local failure situation in the structure [65]. At the second stage, the column stubs left are firmly fastened by reaction frame such that the boundary conditions appear similar to that of a real damaged building. Last, the controlled loading is carried out in load-based and displacement-based ways to investigate the structural behavior under simulated collapse conditions. These steps are used to assure close resemblance of the experimental set-up to real structural behaviour after column loss.

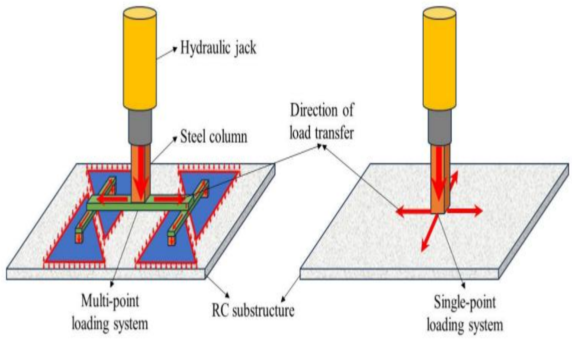

Fig 1. Loading device for quasi-static testing of flat slab column structures.

Such tests have two major loading methods: single-point and multi-point loading. In single-point loading, the force is exerted at the point where the column has been removed hence it is easy and simple to implement. Nevertheless, such an approach tends to cause localized failure like punching shear. Multi-point loading on the other hand spreads the load on multiple points with the use of beams and plates thus being more accurate in depicting distributed loads in the real world [66]. Multi-point loading studies by Qian et al. demonstrated less localised failures and provided better simulation of collapse behaviour [67]. This strategy is also backed by the defense principles and confirmed by the researchers such as Sasani who noted that distributed gravity loads are the ones that control the structural behavior though non-uniform pattern of loads might occur in the course of large deformations.

3.1.2. Dynamic Testing

Quasi-static tests can be used to study the growth of structural resistance in the event of collapse but actual-life studies of failures have shown that the structural damage normally takes place very quickly and in many cases in milliseconds because of the sudden dynamic acts.

It is thus impossible to get the real behavior of structures with abrupt events like the removal of column by the use of the static methods. The limitation restricts the use of dynamic testing in engineering practice. In dynamic testing, dynamic load on the structure is initially simulated by placing heavy masses or suspending heavy loads on the structure. A column is then taken away immediately to examine the mechanism of structural response and load redistribution as a result. This abrupt displacement is typically done by installing either an instantaneous column removal device (ICRD) at the bottom of the column or by discharge of an installed hook system at the top [68].

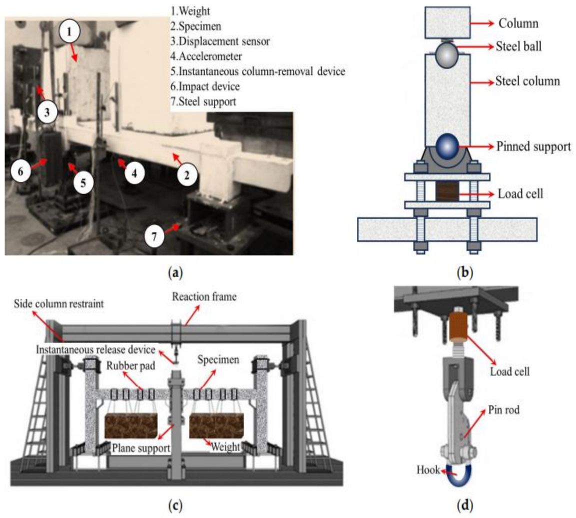

Fig 2. Loading device for dynamic testing of flat slab–column structures. (a) Install an ICRD below [24]. (b) ICRD [24]. (c) Install a hook-based column-removal device from above [25]. (d) Hookbased column-removal device [25].

It has also been shown through experimental studies that instantaneous column removal produces important dynamic effects, such as vibrational effects and higher load demand in the surrounding members of the structure. On the case of column loss in interior, studies indicate that a load on the adjacent columns may increase to approximately 124.8% and in the multi-column case, 117%. Multi-column failures are capable of causing significant displacements than uni-column loss. Also, dynamic effects enhance the material strength because of strain rate, boosting the steel strength by approximately 10 percent and concrete strength by approximately 15 percent. It is also reported that the factors of dynamic amplification are dynamic with a range of approximately 1.09 to 2.6, based on failure scenarios and structural configurations, showing that the application of dynamic behavior is highly important in the progressive collapse analysis.

3.2. Types of Column Failure Scenarios

Accidental and extreme loading conditions may cause Failure of columns in real structural system that are among the major factors that contribute to stability of the structure [69]. Perimeter columns are the most susceptible of all columns because they are the ones that are susceptible to direct external forces such as vehicle collisions, falling debris or aircraft hits. Other extreme conditions that may lead to simultaneous failure of more than one column include earthquakes in addition to impact loads, fire and blast loading [70]. These failures often lead to progressive breakdown where failure of one structural component leads to a domino effect on the rest of the structural components.

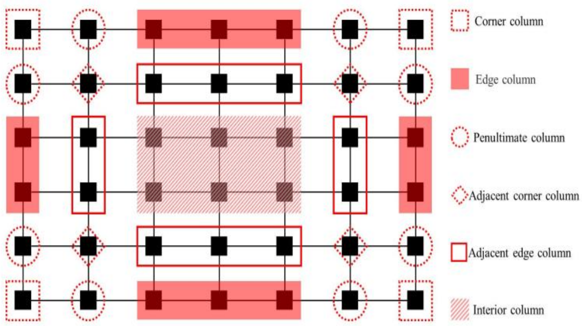

Fig 3. Standardized nomenclature for column failure locations

Interior, edge, and corner column locations have different failure characteristics caused by a change in dissimilar failure features due to a modification in boundary conditions and power of load-sharing. The failure scenario has a direct influence on the redistribution of forces within the structural system and the determination of the ability of the structure to resist the collapse [71]. The standardized recognition of the location of columns is also crucial in the progressive collapse analysis to know where the critical failures will occur to realize safer structural design.

3.2.1. Load Redistribution Capability

The capacity of a structure to comply with redistribution of loads in the event of column failure is heavily dependent on the position that the column removed [72]. The interior column failure allows the greatest redistribution capacity as the column is surrounded by several supporting elements. Research has shown that nearly all the failed column load is shifted to other columns, with edge columns receiving a higher proportion of the failed column load at the beginning. With the enhancement of the deformation, the load is gradually distributed on the corner columns through the formation of the membrane action, thereby improving the structural stability [73].

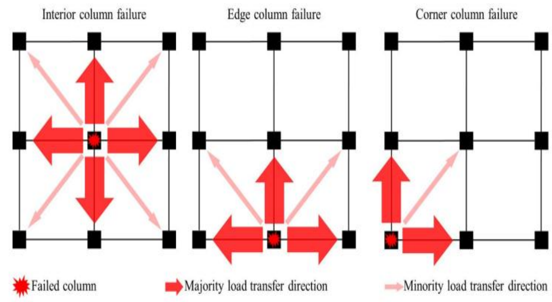

Fig 4. Load transfer mechanisms for different column failure scenarios.

Conversely, edge column failure causes a limited redistribution of loads because of a low-level of support on one side [74]. Most of the load moves in the shorter span direction, whereby the smaller part moves to corner columns as the rest is carried by slab action. Failure in corner column is the worst situation as it would greatly diminish the load redistribution capability because of absence of boundary restrictions. This usually leads to brittle failure at slab-column junctions. In general the interior column failure is more resistant and has higher redundancy as compared to perimeter failure with less structural strength.

3.2.2. Load Redistribution Capability (Dynamic Behaviour Perspective)

The load redistribution in the flat slab systems is not fixed but it changes constantly throughout the collapse process. In the first place, the compressive membrane action holds the leading role, and the loads can be effectively transferred to the columns which are located close to each other [75]. When the structure has gone through additional deformation and when punching shear failure has taken place, tensile membrane action becomes operational through reinforcement mechanisms. The transition allows the building to partially recover its load-bearing capacity and withstand total collapse.

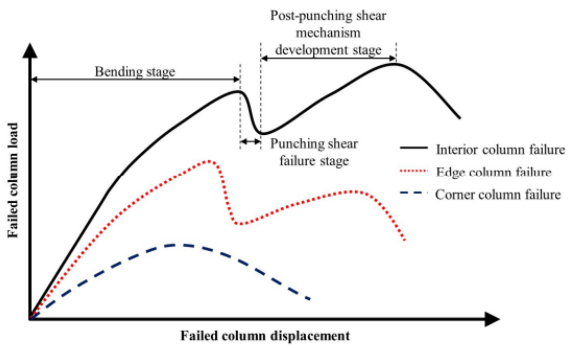

Figure 5. Load–displacement curves for different column failure scenarios.

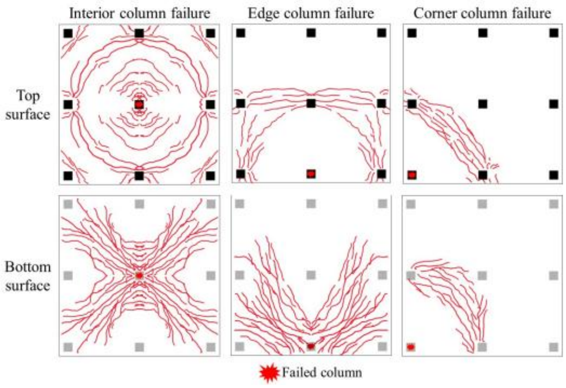

Fig 6. Failure modes for different column failure scenarios

In comparative studies it is found that both the edge and combined column failure cases exhibit the same redistribution pattern with respect to the nebulous columns facing most of the load transferred on them whereas the remote columns contribute the least. The efficiency of redistribution however diminishes greatly in corner column failures because of non-profession of confinement and boundary support. These observations underscore the fact that structural redundancy and continuity plays a major part in enhancing resistance to progressive collapse. Therefore, it is necessary to comprehend the concept of dynamic load redistribution in order to develop safer and more robust flat slab buildings.

3.3. Types of Resistance Mechanisms

Four main resistance mechanisms are of the progressive collapse behaviour of flat slab-column systems; compressive membrane action (CMA), tensile membrane action (TMA), punching shear, post-punching shear mechanisms [76]. It has been demonstrated through experimental studies that these mechanisms work in sequence and occasionally concurrently to oppose structural failure. As pointed out by Zhang (41), CMA has a prevailing role in the last phases of failure, which might be enhanced by maintaining the right boundary conditions and offering continuous reinforcement. Equally, Keyvani et al. (42) noted that in the event of failure of an interior column, large compressive membrane forces that reached about 700 kN/m can occur in the slab, which creates an increase in the load carrying capacity.

Subsequent research suggests that TMA can act as a significant contributor to structural resistance once it has been damaged, as long as enough ductility and edge restraint is present. Park (43) and Regan (44) highlighted that TMA enhances ultimate strength, whereas the works of Qian (17) and Xue (35) showed that TMA and pinning mechanisms could still preserve as much as 70-percent of the peak load after punching shear failure.

Moreover, Yi (46,47) and Huang (36) affirmed that performance is improved by the synergistic action between bending and membrane mechanisms particularly through continuous reinforcement. A study by Yang et al. (37,48) revealed that transition between these mechanisms is caused by various failure scenarios, including corner column loss. Notably, investigations indicate that the residual capacity may be enhanced by correct design of reinforcement by up to 70% of the original capacity to provide better resistance to progressive collapse.

4. NUMERICAL SIMULATION OF PROGRESSIVE COLLAPSE IN FLAT SLAB–COLUMN STRUCTURES

Numerical simulation is important in explaining the progressive collapse of flat slab-column structures [77]. These systems are very susceptible to punching shear failure at slab-column joints because there are no beams, and this can trigger off a series of events that might cause a complete structural failure. High fidelity simulation methods allow the researcher to obtain a realistic representation of the transition between local joint failure and global collapse behaviour [78]. These models are good representations of the concrete damage, stiffness degradation and bond interaction between reinforcement and concrete [79]. The nonlinear analysis allows investigating the mechanisms of redistribution of the load following the removal of columns or the joint failure. Nevertheless, the issue of the balance between the computational efficiency and the model accuracy is also very difficult to attain. Also, parameters like material properties, boundary conditions, and loading scenarios are sensitive and therefore, validation is important in a bid to achieve reliable predictions.

4.1. Types of Simulation Methods

To examine progressive collapse in flat slab-column systems, several numerical simulating techniques have been created [80]. The most common of them is the Finite Element Method (FEM) which has been adopted because of its capacity to simulate complicated material response and nonlinear structure response. There are other methods like the Discrete Element Method (DEM) and explicit and implicit methods of integration which are also used with regard to the accuracy expected. These techniques can be used to give detailed representation of cracking, deformation, and failure mechanisms subjected to extreme loading conditions.

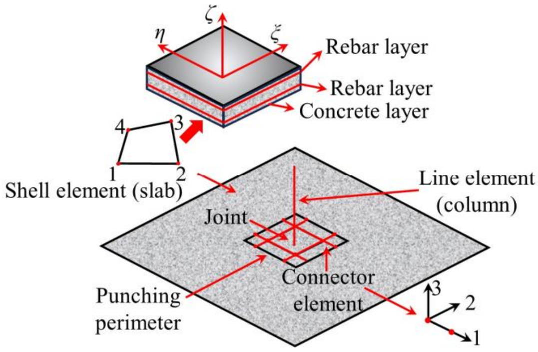

Fig 7. Macro-scale finite element model [76].

In order to enhance the computational efficiency, scholars have proposed simplified modeling techniques that include equivalent frame models, grid systems, and beam-based models. Finite element proposal has been made of a macro-scale model that combines the shell elements and the connection elements to model the behavior of slabs, and joint failure. Bending and redistribution of loads are considered by shell elements, and the separation of slab column joints during the failure of punching is considered using connection elements. Despite a good predictive capability of the models in predicting load-displacement behavior, the use of assumptions, including the assumption of constant shear stiffness, can contribute to overestimation of torsional resistance and joint strength.

4.2. Local Joint Model

Local joint models apply special attention to the correct simulation of slab-column connections as the most important areas in flat slab systems. The models are aimed to model the punching shear failure with concentrated loads taking into account the effects of nonlinear material behavior and joint interactions. The slab is normally modeled with shell elements and special connection elements are employed to model separation between slab and column in the event of failure. The given approach assists in the investigation of the load transfer mechanism and the beginning of failure at the joint level.

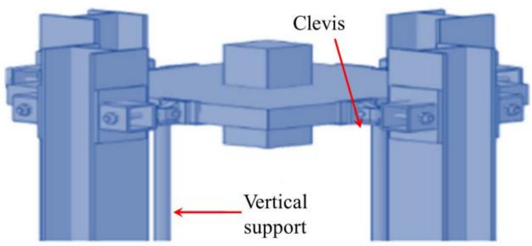

Fig 8. Flat slab–column joint model [89].

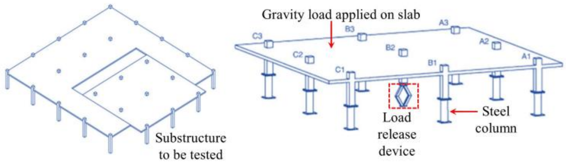

Figure 9. Punching shear model for the flat slab–column joints [90].

As evidenced by advanced researches, the resistance to progressive collapse is highly enhanced by the use of compressive membrane action within the slab. Other models make use of node-to-node connection elements which have many degrees of freedom to simulate realistic joint behavior, both the translational and rotational effects. Geometric nonlinearity under large deformations can also be taken into consideration with these models using revised formulations. The conclusions show that local joint models give a high accuracy in predicting punching shear failure and structural response. They however dictate that parameters should be carefully calibrated and cross-validated with experimental results in order to be reliable.

4.3. Global Structural Model

Global structural models these are simulations that are used to determine the overall behavior of flat slab column structures in the event of progressive collapse. The models combine local mechanism of failure into a complete structural system to examine the redistribution of loads, spreading of collapse, and redundancy in structure. The interaction between reinforcement and concrete is represented by techniques like bondslip modeling and it has a major impact on post-failure behavior. These models can model secondary punching shear failure and structural degradation by minimizing the bending stiffness at key areas.

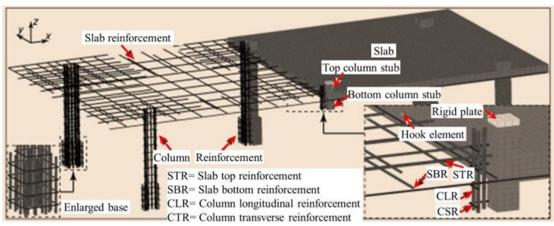

Fig 10. Bond–slip model for flat slab–column structures [93].

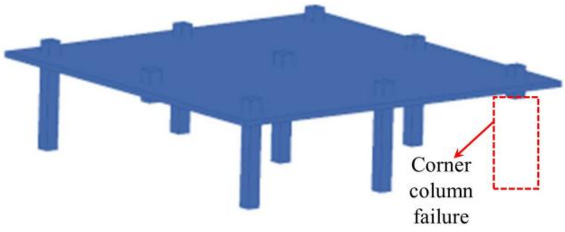

Fig 11. Separate model for reinforced concrete flat slab–column structures.

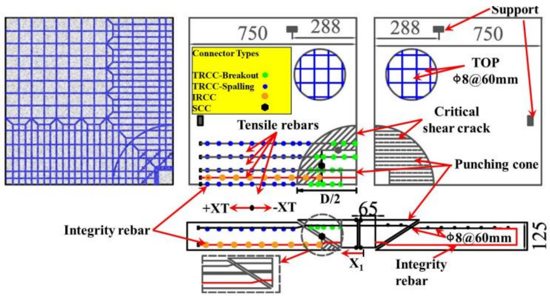

Figure 12. Continuous/separate model for punching shear failure in slab-shell elements before and after failure [42]

The collapse scenarios have been considered using different modeling methods, however, including column removal at interior, edge, and corner positions. Research demonstrates that structures tend to be more resistant in case interior columns fail as compared to corner columns. Moreover, compressive membrane action that is created as a result of constraint of the boundaries increases the punching shear strength and increases collapse resistance. Further models based on the use of software like ABAQUS, LS-DYNA and ETABS have shown that the quality of reinforcement anchorage and structural detailing play a key role in performance. In general, the global models offer a thorough insight into structural behavior, however, they consume a lot of computational resources and need to be modeled thoroughly.

5. CODES PROVISIONS

The disastrous Ronan Point tower gas explosion, structural design codes were considerably changed in order to deal with the danger of progressive collapse in buildings. Several international codes like British Standards, Eurocodes, ACI 318-08, ASCE 7, General Services Administration, and Department of Defense came in with new provisions to improve the structural robustness. Such codes are aimed at avoiding disproportionate collapse by including safety precautions against unforeseen occurrences, including explosions, impacts or structural failures.

As an example, EN 1991-1-7 includes the measures to be taken during the design of buildings to resist accidental loads so that the damage in one area does not spread across the whole building.

Table 1: Summary of Buildings Affected by Progressive Collapse

No.	Building Name	Location	Date	Collapse Cause
1	St Mark's Campanile	Venice, Italy	July, 1902	Fire event
2	Ronan Point Apartment	London, UK	May, 1968	Gas explosion
3	Skyline Towers Building	Virginia, USA	March, 1973	Early framework removal
4	Civic Arena Roof	Kansas, USA	1978	Heavy snow load
5	Pavie Civic Tower	Pavia, Italy	March, 1987	Excavation
6	Ancient Bell Tower	Goch, Germany	1992	Bell dynamic effects
7	Murrah Federal Building	Oklahoma, USA	April, 1995	Terroristic attack
8	Khobar Towers	Saudi Arabia	1996	Terroristic attack
9	World Trade Center	New York, USA	Sept., 2001	Terroristic attack
10	Windsor Tower	Madrid, Spain	Feb., 2005	Fire event

Fig. 13. Some historical buildings subjected to progressive collapse.

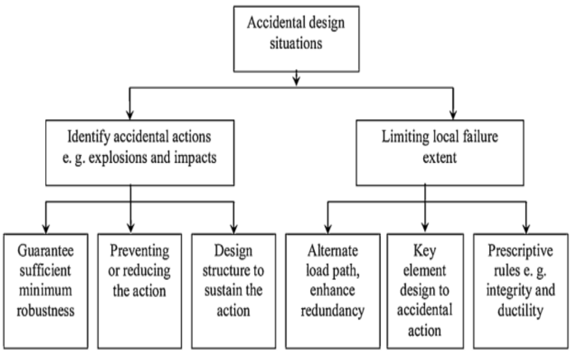

Fig 14. Different methodologies to resist accidental load actions [3].

Specifically, the General Services Administration and the Department of Defense guidelines have specific procedures that can be used to assess the vulnerability of a building to progressive collapse. To simulate the possible failure conditions, the GSA (2013) provided certain column removal cases, such as the case of corner column removal or middle column removal on the edges of the building. Such situations are normally examined at the ground level, because columns on the ground level carry the greatest weight and when they collapse the rest may collapse. These provisions enable engineers to determine the resilience of structure and put the required reinforcement measures to enhance safety and avoid disastrous failures.

Progressive collapse design concept is aimed at avoiding disproportionate collapse of the structure in the case of removal of a critical load bearing member of the structure, like column. Nevertheless, not every building must be made to be under such extreme conditions. It has been stipulated that buildings such as multi-storey buildings above ten storeys have to meet some requirements to cope with progressive collapse. GSA provisions permit a small level of damage, which is failure of panels over the column removed, or collapse within a floor space of approximately 167 m 2. As well, in 2010, the department of defense (DoD) unveiled new guidelines that focused on the different degrees of structural defense. In the case of buildings that have very low levels of protection needs, the safety can be guaranteed by using appropriate horizontal and vertical tie systems that ensure structural integrity.

Table 2: Comparison of Codes for Progressive Collapse Design

Parameter	BS EN	GSA	DoD
Material Increase Factor	Depends on loading rate	Depends on loading rate	Concrete: 1.25Steel: 1.25
Dynamic Increase Factor	Accidental load included	Accidental load included	2.0 applied to entire structure2.0 applied to bays above removed column
Column Removal Storey	Not specified	Not specified	Ground levelEach storey considered
Damage Progression Area Limit	Smaller of:≤ 70 m²≤ 15% floor area above removed column	Smaller of:≤ 100 m²≤ 15% floor area in two storeys above	Exterior column:As per BS≤ 30% total floor areaInterior column:≤ 140 m² (floor above)≤ 334 m² (bay above removed column)

Also, DoD guidelines and GSA guidelines follow a comparable approach to linear static analysis, although they diverge on issues like combinations of loads, and permissible damage. DoD takes into account various column removal cases at each floor level such as interior columns, corner columns, etc. to test structural robustness. In general, three major approaches are identified for progressive collapse prevention.

The purpose of the event control technique is to shield the building against accidental loads. The direct design methodology improves the redistribution of loads by processes such as alternate load paths and reinforcement of the key components. Finally, the indirect design method provides sufficient strength, ductility and continuity by proper detailing and tie systems which serves as a basic protection against collapse.

6. STRUCTURES PERFORMANCE UNDER COLLAPSE

The structural system is redistributed to a large extent when an interior column is suddenly removed. The beams that are not removed above the column that is removed will undergo a sharp increase in bending moment, which is usually reversed and many times less than usual. This causes unforeseen force situations in members that were not intended to be affected by other modes of stress. To eliminate progressive collapse the structure transfers loads to neighboring elements and opens up alternative load paths. These systems allow the structure to be stable and restricting damage spread. Altogether, load redistribution in the framework of providing a structure with adaptability is the important factor which contributes to the increased collapse resistance.

6.1. Vierendeel Action

Vierendeel action occurs in reinforced concrete frames following the removal of columns as a result of the beams, slabs and columns having a double curvature around the damaged area. This causes redistribution of bending moments whereby some of them increase greatly and others being redistributed to the other sides of structural elements. This, contrary to normal conditions where compressive stresses are mostly exerted on the columns, results in tensile stress because of bending. Lateral and vertical reinforcement of the members becomes a requirement to withstand these forces by continuous reinforcement. Structural integrity and resistance to progressive collapse due to proper moment transfer is enhanced by adequate reinforcement especially at beam-column joints.

6.2. Compressive Arch Action

Compressive action is applied on the compressive action where the beams and slabs acquire compressive forces as a result of column removal which is held by other structural elements. Such restraint enables the structural members to act as an arch to distribute the loads through compression instead of bending. At low deflections, this mechanism improves greatly load-carrying capacity and postpones structural failure.

It has been established through experimental studies that compressive arch action is capable of increasing resistance by significant amount making it one of the most effective ones during the initial stages of deformation.

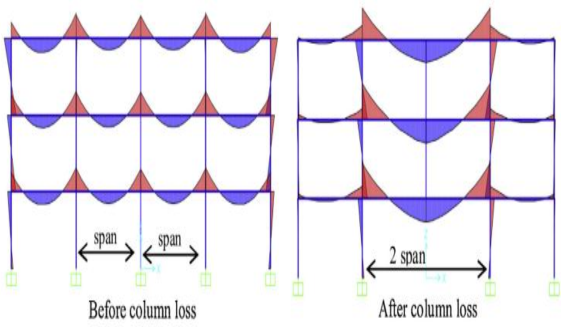

Fig 15. Bending moment redistribution in a frame after internal column removal.

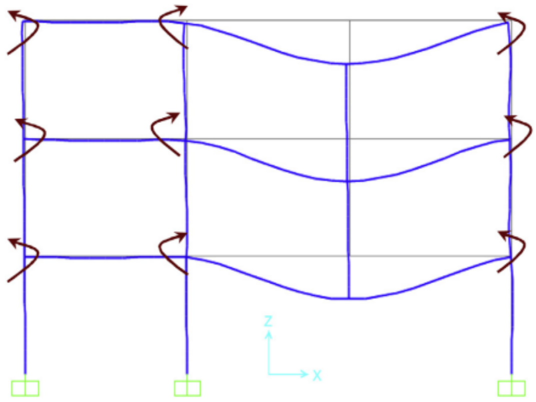

Fig 16. Vierendeel action in moment a resisting frame.

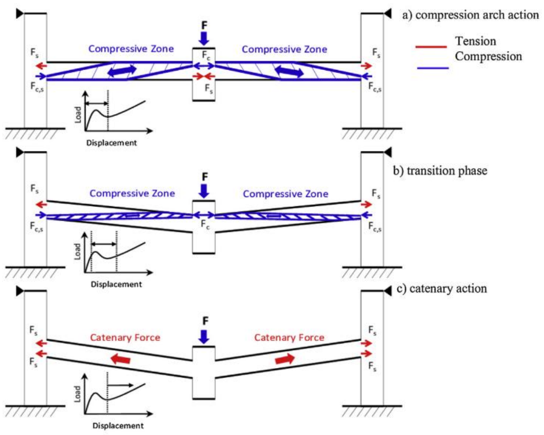

Fig 17. Compressive arch action and catenary action [30].

The greater the deflection, the greater the contribution of the arch action is inhibited by gradual diminution of the effectiveness of horizontal restraint. The reinforcement percentage and span-to-depth ratio are some of the factors that determine the strength acquired by this mechanism. Members whose depths are larger and reinforced ratio is low are more likely to enjoy compressive arch action. According to research findings, this mechanism has the capability of enhancing the vertical load capacity in a significant capacity, particularly in beams with adequate end restraints. Thus, compressive arch action should be known and approximately included in the design of buildings that can withstand progressive collapse.

6.3. Catenary Action

Catenary action occurs at high deflections as the beams and slabs change their bending to tensile resistance of force. At this phase, the structural components are used as tension cables with the longitudinal reinforcement bearing the load by means of tensile forces. The vertical element of this tension force is used to overcome weight of other loads following loss of the column. This action only takes place when the members are deformed and rotated enough. Constant reinforcement, good anchorage, high catenary action and high joint ductility is necessary to maintain correct catenary action. It enables the structure to experience massive deformations without experiencing an unexpected collapse.

6. DISCUSSION

Discussion of progressive collapse behaviour in reinforced concrete (RC) buildings brings out the fact that structural robustness is not solely determined by the strength of members but also by the capacity of the system on the whole to redistribute the loads after local damages. The paper under consideration shows that flat slab-column structures are especially susceptible because of the mechanisms of direct loads transfers and the lower redundancy, and slab-column joints are the most critical areas of failure initiation. Both experimental and numerical evidence shows that column removal, particularly corner and edge removal, is associated with extreme stress concentration and low redistribution potential, and interior column removal is associated with a relatively higher amount of redundancy. The analysis also establishes that the level of structural response under dynamic effects is extensive, and increases in loads are greater than 120 percent and amplification factors of dynamics rise to as much as 2.6, thus highlighting the inefficiency of the strictly static analysis approach.

Mechanisms of resistance compressive membrane action, tensile membrane action, and post-punching behavior are sequentially but overlappingly involved in postponing collapse and with research showing residual capacities of 70% when reinforcement continuity is properly provided. The nonlinear finite element methods are effective to simulate cracking, stiffness degradation, and bond-slip behavior, but also the accuracy is very sensitive in relation to modeling assumptions and parameter calibration. Also, structural configuration, slab type, beam depth, soil to structure interaction, and material deterioration (corrosion) also have a great impact on collapse resistance. GSA and DoD code provisions underscore the use of the Alternate Load Path (ALP) method that has been demonstrated to be effective in assessing structural resilience when faced with hypothetical conditions of damage. Nevertheless, it is shown in the discussion that, in spite of the development of experimental, analytical and computational methods, there is yet to be a unified system of applying the local joint behavior with the global structural response. Consequently, the future needs are that, the multi-scale modeling, better characterization of materials, and performance-based design strategies should be in future researched in order to increase reliability and safety of the RC building against progressive collapse.

7. CONCLUSION

The research concludes that the collapse behavior of reinforced concrete (RC) structure is progressive majorly due to the capacity of the structure to redistribute the loads and continue alternate load paths following localized failure. Flat slab column systems are classified as very susceptible because it can easily collapse through punching shear failure at joints; thus spreading collapse quickly. Both experimental and numerical findings reveal that the dynamic effects cause enormous impact on structural response where load amplification measures between 124.8 per cent interior column removal and 117 per cent multi-column failure, whereas dynamic amplification factors range between 1.09 and 2.6. Compressive membrane action (CMA), tensile membrane action (TMA), and post-punching behavior are the resistance mechanisms that increase the structural capacity whereby membrane forces have values of approximately 700 kN/m and residual strength retention increase to approximately 70 percent with appropriate reinforcement detailing. Comparative literature indicates that the interior column loss is more advantageous in providing more redundancy and the corner column failure results into critical behavior of brittle nature as a result of the restricted boundary support.

Also, slab type, beam depth, soil-structure interaction and material degradation, among others have a significant influence on collapse resistance with certain cases recording displacement values of up to 130 mm when the structure is subjected to actual collapse. The provisions of the code, including GSA and DoD, suggest the Alternate Load Path (ALP) approach and allow damage to be minimized in terms of area (e.g. 167 m 2 or less) to prevent injuries. In general, the paper highlights that there is a need to enhance ductility, continuity, and redundancy to facilitate structural robustness and eliminate disproportionate collapse during structural collapse of RC buildings.

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