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PROGRESSIVE COLLAPSE OF MULTISTOREY FRAME STRUCTURES- A CRITICAL REVIEW

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Abstract

This paper presents a thorough review of the progressive collapse of multistory buildings. firstly, the concept and disastrous events that led to the progressive collapse of the multistorey structure have been thoroughly examined. Analysis of progressive collapse in reinforced concrete and steel-framed multi-storey buildings under column removal scenarios in accordance with design codes were examined. The causes of gradual collapse in multistorey structures include, but are not limited to, design or construction errors, explosions, fires, traffic collisions, and seismic waves. To offer comprehensive theoretical insights, numerous design methodologies and codes have been examined, including the Alternate Load Path, Finite Element Analysis, and Applied Element Method. To prevent progressive collapse, the implementation of structural dampers and the reinforcement of beam-to-column connections are viable structural mitigation techniques to consider. Ultimately, the disastrous event of progressive collapse in multistorey buildings can be alleviated through appropriate design methods and construction adhering to the guidelines established in various design codes.

Key words: collapse, multistorey, buildings, progressive, concrete, steel.

1.0 Introduction

Following the collapse of the Ronan Point Apartment Tower in 1968 in East London, significant attention has been directed into research on strategies to prevent building collapse catastrophes. The terrorist assaults on the Alfred Murrah Building in 1995 and the World Trade Center in 2001 prompted the creation of preventive measures against progressive collapse. The General Services Administration (GSA, 2013, p. C2) defines "progressive collapse" as the propagation of an initial localized failure from one element to another, ultimately leading to the collapse of a whole structure or a significant component thereof.

Progressive collapse in structures is frequently initiated by initial damage to structural elements. Potential causes include excessive structural loading, vehicular collisions, terrorist activities such as bomb detonations, foundation failures, seismic events including earthquakes, gas explosions, and defective construction practices. The loading pattern and boundary conditions of structural members are frequently modified by excessive loading circumstances, often leading to failure in the elements. This imposes an urgent structural demand on the remaining components of the structure to achieve stability. These additional features pursue alternative load routes to redistribute the imposed load on the structure and avert failure. Nonetheless, failure may transpire in the remaining structural components if their load-bearing capacities are surpassed, resulting in progressive collapse (Salem et al., 2011).

The United Kingdom was the first government to establish specific rules for addressing progressive collapse, as outlined in the code BS5950-1 (2001), which recommended the interconnection of structural elements. Consequently, numerous countries have established design codes to avert increasing structural collapse. These rules provide directives for design to improve structural resilience against progressive collapse. Multiple design factors are addressed in the codes. Kwasniewski (2010) emphasized that the analysis of progressive collapse in multistorey buildings must consider three aspects: loading arrangement, global failure criteria, and appropriate analytical tools. The diverse country codes encompass these factors.

The collapse of multistorey structures has been a significant difficulty in construction, leading to the loss of lives, property, and resources. Therefore, it is essential to comprehend the reasons and mechanisms of progressive collapse, as well as the preventive measures that should be adopted to limit its occurrence in multistorey buildings.

Numerous independent research have been conducted to examine the causes, mechanisms, and effects of gradual collapse under diverse settings. Nonetheless, there exists a paucity of research offering a thorough examination of the reasons, mechanisms, and preventive strategies related to the progressive collapse of multistorey structures.

This research aims to analyze the mechanisms of progressive collapse owing to excessive loading and identify preventive measures implemented to avert progressive collapse in multistorey buildings.

2.0: Review on Previous Studies

2.1 Progressive Collapse Analysis of Reinforced Multistorey Concrete Buildings

Utilizing the applied element method (AEM), Salem et al. (2011) conducted an economic design for reinforced concrete structures to mitigate the risk of progressive collapse. The study employed nonlinear path-dependent models for concrete and reinforcing bars. The study employs a model based on ACI 318-08, focusing on the effects of removing one or more ground floor columns to analyze the reaction of conventionally constructed multi-story reinforced concrete structures. The model is utilized to forecast post-failure responses, including falls, collisions, and element separations. Subsequently, the model was executed iteratively to ensure a secure architecture against progressive collapse.

The study's results indicated a comparative advantage of the AEM analytical method over the finite element method (FEM). The work demonstrated that the collapse zone may be determined in a singular analysis utilizing the AEM, accounting for element separation and failure, material nonlinearity, structural part collisions, and significant deformations. In comparison to the linear elastic finite element method, the AEM method demonstrated that around 50% less reinforcement would be necessary to build a system capable of withstanding progressive collapse.
The study demonstrated that the failure of a central column on the ground floor of the reinforced concrete structure would not lead to a progressive collapse of the entire structure. The progressive collapse witnessed in one-third of the structure was triggered by the failure of two central ground columns.

Similarly, the AEM was utilized to quantitatively evaluate the potential for progressive collapse of multistory reinforced concrete framed structures subjected to fire exposure by Elbayomi & Salem (2019). The AEM was validated for evaluating structures subjected to fire loads, and parametric tests were conducted with the Extreme Loading for Structures (ELS) commercial software. The study analyzed parameters like compressive strength, reinforcement ratio of columns, maximum fire temperature, yield stress of steel, orientation of edge columns, and location of fire. The study's results indicated that reinforced concrete structures exhibit substantial resistance to progressive collapse under fire loads.
The AEM was utilized to conduct a numerical evaluation of the progressive collapse of a ten-story post-tensioned reinforced concrete flat slab structure by Mahrous et al. (2020). The structures were developed in accordance with the ACI 318-14 code, and the progressive collapse study was conducted following the DoD guidelines. The time history analysis was conducted with the ELS commercial program. Various instances of column elimination were demonstrated.

The study's results indicated that all instances of column removal conformed to the DoD guidelines, with the exception of the interior column removal on the bottom floor and the edge column removals on the ground, fifth, and tenth floors. Upon the removal of the interior ground column, the structure experienced partial collapse owing to compression failure, as the compressive load surpassed the column's ultimate axial load limit. Upon the removal of the edge shear, a partial collapse transpired in the region adjacent to the wall. This occurred because to the substantial area of the slab linked to the edge shear wall in comparison to those connected to the edge columns. The removal of the edge column precipitated a collapse caused by punching shear in the slab at the neighboring corner column. The results indicate that the structure is capable of withstanding progressive collapse. A subsequent investigation on the seismic impact on the progressive collapse of the structure was recommended.

De Biagi et al. (2017) employed the column removal methodology to model the progressive collapse of reinforced concrete structures by implementing three distinct strategies: reduction of damaged column mechanical properties, incremental loading following the removal of damaged columns, and incremental unloading of internal forces in damaged columns. Nonlinear static studies were conducted on the engineered structure. The results indicated that the ductility of the construction in the various scenarios was enhanced. However, there was no assurance of robustness against increasing collapse. Alshaikh et al. (2019) conducted an experimental investigation to investigate the enhancement of deformability and ductility in reinforced concrete frames and their resistance to progressive collapse. The reinforced concrete was formulated by partially substituting fine aggregate with waste crumb rubber at a volume concentration of 20%. The ductility, failure mode, load-displacement behavior, fracture pattern, and mechanical properties of the control and reinforced concrete frames. The experimental results indicated that substituting 20% of the fine aggregate with rubber crumb enhanced the ductility of the reinforced frame. Nonetheless, the use of leftover rubber crumb diminished both the compressive strength and tensile strength. The results indicated that the deflection in the rubberized frame exceeded that of the conventional concrete control. The study concluded that rubber crumb could avoid progressive collapse by enhancing the ductility of concrete frames.

2.2 Progressive Collapse Analysis of Steel-Framed Multistorey Buildings

Liu (2010) developed nonlinear finite element models and utilized them to assess the post-attack performance of both original and retrofitted beam-to-column connections using the ABAQUS finite element program, aiming to enhance the catenary action of steel structures to avert progressive collapse. The models were executed on one-, two-, and three-dimensional solid elements exposed to catenary stress. The results obtained were checked with the literature and validated. The comparative results indicated that the connection in the original structure was insufficiently robust for catenary action. Nonetheless, the retrofitted connections generated supplementary bending moments transmitted from the beams to the column when the joint is reinforced. This led to improved resistance to progressive collapse in the retrofitted structures.

Another study by Meng et al. (2018) investigated the anti-collapse performance of several beam-to-column assemblies comprising two beams and three columns. The investigation involved static loading testing on unreinforced flange-bolted web-connected steel specimens with three span ratios: 1:0.6, 1:1, and 1:1.4. Numerical simulations were performed on the specimens. The experimental analysis indicated that the fracture of the tension flange attached to the failure column began the failure in the specimens. This was succeeded by the fracture of the tension flange at the beam's attachment to the adjacent side column.

An enhanced anti-progressive collapse performance was noted with the equal-span ratio due to the synergistic effects of the lower and higher beams under substantial strain. In the unequal span beams, the shorter beam failed before to the longer beam, as the load peaks diminish with an increase in loading displacement. Nevertheless, analogous patterns in deformation, anti-collapse mechanisms, and the sequential emergence of the flexural phase, flexural-to-catenary transition phase, and catenary action phase were noted for all span ratios examined in the study.

Zhong et al. (2017) conducted a study examining the anti-collapse performance of steel frames with different stiffness connections. The study examined three distinct connections: welded unreinforced flange-bolted web connection, top-seat angle with double web angle connection, and double web angle connection, all subjected to internal column removal using the APM analytical approach. The study conducted model tests and numerical analyses to ascertain the failure modes, load-deformation responses, and mechanical behavior of the steel frame.

A fracture occurred with various disruptions, and intermittent damage was noted in the tension flange linking the respective column in the welded unreinforced flange-bolted web connection. The failure in the top-seat angle with double web angle connection resulted from the fracture of the tension angles linking the beams and column. In the double web angle connection, the specimen's failure was identified by the fracture of the double web angles at the bolt hole. During the catenary mechanism phase, flexure-catenary mechanism phase, and flexural mechanism phase, the specimens with welded unreinforced flange and top-seat double web angle connections exhibited an identical anti-collapse mechanism process. The double web angle connection specimen experienced a flexure-catenary mechanism phase followed by a catenary phase, with its resistance primarily governed by catenary action. The researchers observed that the top-seat double web angle connection could utilize the beam-end rotation and axial tensile forces in the later stages, thereby achieving enhanced bearing capacity due to the combined effects of catenary action and flexural action under significant deformations.

The study examined the impact of peripheral components on the anti-collapse performance of the assembly in various connections using validated numerical models. The results indicate that if the restrictions from the side columns sufficiently facilitate catenary activity in the beam, there may be minimal impact on enhancing the structural load-bearing capability against collapse. The impact of mega-thrust, crustal, and subduction earthquakes on the seismic resilience of a moderately ductile concentrically braced frame (MD-CBF) multistory building in Canada was assessed on-site. Nonlinear dynamic assessments were conducted on numerical models derived from structural frameworks utilizing data from the 2011 Mw9 Tohoku subduction earthquake and other globally documented crustal earthquakes. Four-storey, eight-storey, and twelve-storey MD-CBF structures were assessed using OpenSees (Tirca et al., 2015). The investigation revealed that the geotechnical parameters of the site aligned with the selection criteria for subduction records of the March 2011 Mw9 Tohoku earthquake. The suggested numerical models can recreate the nonlinear seismic response of all building sets examined, from yielding to failure, during subduction and crustal earthquakes.

The highest demand was observed on the same floor, predominantly on the lower two floors, during both crustal and subduction earthquakes in the 8-storey and 12-storey MD-CBF structures. In the four-story MD-CBF building, the highest demand was observed on the top floor during a subduction earthquake and on the bottom two floors during a crustal event. The collapse margin ratio and adjusted collapse margin ratio of the various MD-CBF buildings were approximately 150%

greater under the crustal record set than under the subduction record set, as assessed for collapse safety using FEMA P695. This indicates a greater margin of safety for MD-CBF buildings during crustal earthquakes compared to subduction earthquakes. Tian et al. (2018) investigated the anti-progressive collapse mechanism of eight full-scale long-span single-layer spatial grid structures by experimental and numerical methods. The load-displacement reactions, strain measurements, failure mechanisms, and experimental findings were examined as a static loading testing device for spatial loading was designed. The examinations were conducted on the spatial components at various angles. The results indicated that at a 0-degree slope, the beam mechanism supplied load resistance at displacements under 50 mm, whereas displacements over 150 mm relied on the catenary mechanism for vertical load bearing capability. At a 30-degree inclination, the displacement was minimal, and compression mechanisms were established. The researchers also observed the translation of the beam and catenary mechanism to a compression mechanism with member inclinations above 5 degrees. Comparable outcomes were attained in the numerical analysis.

While conventionally braced CBFs can avert progressive collapse during seismic events, they may incur significant time and financial losses due to necessary repairs. Shape memory alloys (SMAs) have been utilized in the construction of multistorey buildings to address these challenges, due to their significant deformation recovery properties and energy dissipation capabilities. Consequently, Qiu and Du (2020) assessed the seismic performance of concentrically braced frames (CBFs) utilizing a novel brace known as the recentering energy dissipative brace (REDB), which integrates shape memory alloys (SMAs) for self-centering capacity and steel bending plates to enhance damping. This study aimed to ascertain whether the REDB could surpass the performance of buckling-restrained brace frames (BRBFs). The hysteretic characteristics of BRBFs and REDBFs were investigated using a single-degree-of-freedom system. Furthermore, to achieve a comparable peak response to that of the buckling-restrained brace (BRB) system, the initial yield strength and stiffness of the REDB were adjusted. To corroborate the experimental findings, both static and dynamic assessments were conducted on a prototype six-storey frame structure.

Some observations made from the study include the following;

- The capacity of REDB to regulate maximum displacement and acceleration to levels equivalent to those of buckling-restrained bracing, as demonstrated by the single-degree-of-freedom study.

- Well-engineered REDBs integrate the advantages of BRBs and self-centering braces (SCBs), regulating maximum interstorey drift ratio while capping maximum acceleration and eliminating residual interstorey drift ratio, respectively.
- The REDBF demonstrated superior responses compared to the similar BRBF, as shown by the parametric study.

Kwasniewski (2010) conducted nonlinear dynamic finite element simulations to analyze the gradual collapse of an 8-story steel-framed building at the Cardington Large Building Test Facility in the UK, utilizing the GSA standard. The LS-DYNA commercial software was utilized to conduct the study. The study's results indicated that the structure demonstrated a minimal likelihood of gradual collapse. Bae et al. (2008) investigated the potential for progressive collapse in a three-story cold-formed steel framed construction. The study analyzed five distinct examples in accordance with the methods specified in the GSA and DoD guidelines for the removal of external wall columns, corner wall columns, and subsequent removal analysis. The SAP2000 commercial software suite was utilized for finite element modeling and analysis. The study's results indicated that the elimination of stud columns in the corners could result in a progressive collapse of some sections of the building. The incorporation of stud columns at the corners improved the structure's resistance to progressive collapse owing to their compressive strength. The elimination of the outer columns could not result in the progressive collapse of the structure. Mahmoud et al. (2018) conducted a study examining the seismic impact on the gradual collapse of a 5-story moment-resisting and braced frame structure. The study's design adhered to Egyptian local requirements regarding damage induced by seismic activities. In accordance with DoD rules, a first-story column at a designated place was eliminated using the APM. A three-dimensional time-history analysis was conducted using SAP2000 to execute a parametric investigation.
The biggest displacement was noted with the removal of internal columns in moment-resisting frames, while the greatest displacement occurred with the removal of corner columns in braced frames. Parthasarathi et al. (2019) examined the response of a three-dimensional, four-storey moment-resisting steel structure to progressive collapse under different

temperature conditions. The analyses were conducted in compliance with GSA criteria. Nonlinear dynamic analysis was conducted using ABAQUS, wherein corner, middle, intermediate, multiple corner, and multiple intermediate columns were individually exposed to various temperatures. The results indicated that displacement in the frames escalated with rising temperature, but stress, axial load, and shear load diminished concurrently with the temperature increase. The greatest distortion was noted in the intermediate column. The augmentation of the cross-sectional area of steel and bracing within the frame improved the structure's resilience to progressive collapse.

2.3 Energy-Based Approach of Progressive Collapse Analysis

In previous sections, the analyses of the progressive collapse in the structure were carried out with respect to load (force) and deformation (stress, strain and deflections). In addition to the force- and deformation-based methods for evaluating the dynamics of progressive collapse, there exists the energy-based approach. This approach excludes the concepts of stress and strain. The structural failure is examined through the energy distribution and flow within the structural components resulting from vibratory motions.

The energy-based approach is an innovative methodology introduced by Szyniszewski and Krauthammer (2012). The study presented an energy-based methodology for evaluating multistorey buildings. The study contrasted the outcomes of the method with the traditional force and deformation approaches documented in the literature. The study indicated that progressive collapse in a structure, from an energy perspective, occurs when the structure fails to disperse all the kinetic energy conveyed within the system. The total dissipation of kinetic energy eliminates transitory motions in the structure. This improves the structural stability. Nevertheless, insufficient energy dissipation may cause deformation of one or two structural components, potentially leading to progressive collapse.

The studied research indicates the potential for gradual collapse under different load circumstances. The evaluation emphasized several analytical techniques for assessing the causes and spread of failures in structural elements that could result in the progressive collapse of an entire structure or a substantial portion thereof. The analysis disclosed several strategies to prevent progressive collapse. These are elaborated upon in detail in the subsequent section of this study.

3. Causes of Progressive Collapse in Multistorey Buildings

3.1 Design/Construction Error

Design and construction errors result in structural failure. This transpires when there is a flaw in conception, analysis, and execution. They arise even with the involvement of experienced engineers in the design and construction; they are typically attributed to human errors. Errors in load consideration during design may lead to structural overloading, potentially causing member failure and subsequent progressive collapse.

3.2 Explosions/Blasts

The repercussions of gas explosions in pipelines and bomb detonations profoundly affect structures. In urban environments, such explosions and blasts have caused the slow collapse of structures. Explosions and blasts propagate disturbances (vibrations) into the structural frameworks of the edifice. Insufficient energy dissipation may induce significant deflections in the structure, perhaps causing the breakdown of one or two members and resulting in progressive collapse.

3.3 Fire

When multistorey buildings experience fire, temperature increases produce deformation, strains, and stresses in the structural elements. Fires in certain areas of the building's structure might trigger progressive collapse.

3.4 Vehicular Collision

Vehicular collisions with buildings produce impact loads on the structural elements, potentially resulting in the failure of key load-bearing components and thus leading to gradual collapse.

3.5 Seismic Wave

Seismic waves generated by earthquakes are primary contributors to structural failure. Significant vibration amplitudes are conveyed into building structures, resulting in substantial deformations, strain, and stress within the structure. These structural deformations and pressures lead to the failure of components and potentially the entire structure.

4.0 Design Methods/ Design codes and Mitigation measures

4.1 Analytical Methods of Progressive Collapse

Analyses are conducted to assess the risk of progressive collapse in structures to avert failure. Structural components are evaluated based on catenary or compressive arch actions, alternative load pathways, connection redundancy and robustness, and the tensile forces of structural parts (GSA, 2000). Researchers have utilized many approaches to assess the mechanisms of progressive collapse.

4.1.2 The Alternative Load Path Method (APM)

A prevalent technique is the alternative load path method (APM). This method involves the removal of the critical gravity load-bearing part (column) while establishing a new equilibrium system by the redistribution of internal forces within the remaining structure (GSA, 2013). Upon the removal of the essential gravity load-bearing column, the neighboring beams produce a bending moment to counteract the vertical load. The axial loads of the beam endure and redistribute external forces when vertical displacement escalates. The axial force also adds to the catenary action, which offers resistance against the eventual collapse of the structure. Catenary movement is mostly contingent upon the beam-to-column connection. Consequently, the beam-to-column connection dictates the structural failure (Liu, 2010).

4.2 The Finite Element Method (FEM)

The finite element approach is a computational technique utilized for addressing various engineering challenges. This method involves discretizing a continuum into a finite number of components, with the continuum's attributes derived from the assembly of the properties of the discretized elements. They are employed to provide information regarding failures, stresses, and deformations. Two primary methodologies, linear and nonlinear, are employed, with the former being the most straightforward and widely utilized approach. Both methodologies are applied to static and dynamic issues. Nonetheless, the nonlinear method yields more precise results than the linear approach (Kwasniewski, 2010). The nonlinear dynamic analysis, sometimes referred to as time-history analysis, is the most advanced and precise technique for evaluating progressive collapse. Nonetheless, certain intrinsic obstacles arise in its implementation. Challenges encompass numerical convergence, inelastic characteristics and damage represented by material models, the scale of finite element models for extensive structures, and mesh resolution requirements (GSA, 2000). Despite the robust and well-established nature of the FEM, it is not an optimal analysis method for progressive collapse. This arises from some challenges associated with its application to the investigation of gradual collapse. The analytical procedure utilizing FEM is a sophisticated, iterative technique. Iterative procedures frequently result in convergence errors, which subsequently affect the accuracy of the final analytical conclusions. Furthermore, the research indicates that the Finite Element Method (FEM) is incapable of assessing element damage, separation and detachment of structural components, as well as the collisions and resultant forces between these components. Numerous writers have employed the finite element method to investigate the progressive collapse of multistorey buildings as follows:

Brown et al. (2019) investigated the gradual collapse of multistorey reinforced concrete buildings under a single column removal scenario via a non-linear finite element method and proposed several effective mitigating methods.

Elkady et al. (2024) conducted an extensive assessment of the current advancements in progressive collapse analysis and future outlooks for both rookie and expert engineers and researchers.

4.3 The Applied Element Method (AEM)

The AEM analytical approach for progressive collapse is a stiffness-based technique that employs discrete cracking for structural modeling. The modeled structure is presumed to be an assembly of tiny elements, virtually split and interconnected at the surfaces by normal and shear springs that reflect loads and deformations (Salem et al, 2011). Nonlinear path-dependent constitutive models are employed in AEM Analytical approach. The elasto-plastic model is utilized in compression scenarios, whilst the linear stress-strain relationship is applied in tension circumstances. In the AEM, the equilibrium equation comprising the stiffness, damping, and mass matrices is solved nonlinearly for displacements and rotations. The implicit solution derived for the equilibrium utilizes the method established by Newmark-Beta time integration (Bathe, 1982; Chopra, 1995). In contrast to the FEM, the AEM facilitates the automatic identification of structural separation and contact. The collision forces between the elements can be effectively quantified using AEM. The AEM has been utilized to examine the complete failure of multistory structures (Meguro & Tagel-Din, 2001; Park et al., 2009; Salem et al., 2011) and to evaluate the resistance of multistory reinforced concrete under fire load (Elbayomy & Salem, 2019).

4.4 Design Codes for Progressive Collapse

Salem et al. (2011) state that design guidelines for assessing progressive collapse consider the load-path and the subsequent alterations in the structure's shape. They observed, however, that the codes do not address the root cause of the initial damage; thus, the analyses are independent of the threats. This section discusses several of the most commonly utilized codes.

4.4.1 The ACI Code 318-08

In the design to mitigate progressive collapse, ACI 318-08 posits that enhancing redundancy and ductility of reinforcement can localize damage to the primary load-bearing element, thereby preventing the propagation of failure to other members and improving the overall structural stability. This algorithm relies heavily on the structural integrity of components to avert gradual collapse (ACI, 2008).

4.4.2 The GSA Guideline

This guideline employs the APM (removal of columns) to assess the possibility for progressive collapse. The guideline outlines the analytical procedure for the removal of the load-bearing column. The GSA guideline mandates that the design of a resilient structure, capable of withstanding progressive collapse, must incorporate redundancy, resistance, structural integrity, and ductility. The guideline specifies requirements on the maximum permissible collapse area that may result from the failure of a column (GSA, 2003).

4.4.3 The American Society of Civil Engineers (ASCE) Code

The ASCE Code recommends two alternate design strategies for resisting progressive collapse: direct design and indirect design. The direct design method incorporates the objective of ensuring resistance to progressive collapse during the design phase. It employs either the alternative load-path approach or the unique local resistance technique. The direct design method yields a definitive design solution. The indirect design method indirectly offers resistance to progressive collapse by ensuring minimal levels of ductility, strength, and continuity. The indirect design indicates that the gradual collapse of structures can be mitigated by restricting the propagation of local collapse to other structural components (ASCE/SEI, 2005).

4.4.4 The Unified Facilities Criteria (UFC)/Department of Defence (DoD) Guideline

This code integrates the indirect design approach and the tie force method to enhance resistance to progressive collapse in the structural components of multi-story buildings. The rule mandates that the minimum tie force must be fulfilled in either the horizontal or vertical directions, or in both directions of the building. For structures necessitating medium to high levels of protection, the direct design method is employed in conjunction with the APM, analogous to the GSA requirements. In contrast to the GSA guideline, which permits column removal solely at the bottom floor, the DoD guideline allows for the removal of primary load-bearing columns on each floor (DoD, 2005).

4.5 Strategies for Mitigating Progressive Collapse

4.5.1 Use of Damping Devices

Fuse-like dampening devices may be utilized to improve the seismic safety of structural elements, particularly at their connection points. These dampers dissipate a significant amount of seismic energy during impact by hysteretic movements, redirecting plastic damage from the frame elements to the fuse elements (Christopoulos et al., 2006; Soong & Dargush, 1997). Examples of dampers utilized in the prevention of progressive collapse encompass friction dampers (Dao et al, 2019; Mualla & Belev, 2007), metallic yield dampers (Li et al, 2018a; Qiu et al, 2019a), buckling-restrained braces (BRBs) (Dehghani & Tremblay, 2018; Qu et al, 2018), and recentering energy dissipative braces (REDB) (Qiu & Du, 2020).

4.5.2 Concrete Reinforcement

The resistance of concrete structures to progressive collapse has been improved by reinforcing concrete with fiber materials. The ductility, strain capacity, and deformability have been enhanced with concrete reinforcement. Enhanced ductility increases the energy absorption capacity of concrete, hence diminishing the likelihood of progressive collapse. Orton et al. (2009) proposed the utilization of carbon fiber reinforced polymer to enhance concrete's resistance to progressive collapse. In a comparable study, Elsayed et al. (2016) advocated for the implementation of partial de-bonding of reinforcing rebars to enhance concrete resilience. The ductility, deformability, and strain capacity of concrete frames were enhanced by the partial substitution of fine aggregate with waste rubber crumb (Alshaikh, 2019).

4.5.3 Beam-to-Column Strengthening

Progressive collapse in steel structures can be mitigated by enhancing the beam-to-column connection from simple joints to rigid joints by retrofitting. The beam ends are constrained against rotation at the connection points to the columns. This facilitates the passage of axial forces from the beams to the columns, hence augmenting the moment resistance of the beam. Liu et al. (2010) conducted a nonlinear finite element analysis of the post-attack resistance capabilities of conventional fin plate joint steel frames and retrofitted joint steel plates. The results indicated superior performance by the modified structures.

5.0 Conclusion and Recommendation

5.1 Conclusion

This paper presents a narrative review of literature assessing the progressive collapse of multistorey buildings, identifying the causes, analytical methods, and preventive mechanisms to resist such collapses. The analyzed literature identifies the probable causes of progressive collapse as design and construction deficiencies, explosions, fires, traffic collisions, and seismic events. These exert an influence on the structural components, potentially causing the failure of one or two principal load-bearing members, which may result in the total collapse of the structure or a significant portion thereof.

The reviewed literature has studied the potential for gradual collapse through various experimental and analytical methods. The predominant methods utilized include the alternate load path method (APM), finite element method, and applied element approaches. The alternative load path approach may be executed experimentally and via computer simulations.

The review indicates that the concept of progressive collapse has been incorporated into various design codes, including the GSA guidelines, ACI Code 318-08, ASCE Code, and DoD guidelines, which have been established for the analysis and design of resilient structures capable of withstanding progressive collapse. Moreover, research has led to the development and implementation of enhancements to mitigate progressive collapse in multistorey buildings constructed of concrete and steel. These approaches encompass the reinforcing of concrete with fibrous materials to improve ductility, deformability, and strain capacity, the use of damping materials in joints to absorb energy that may induce deformations in elements, and the fortification of beam-to-column connections. These methods have improved the resilience of structures and diminished the likelihood of progressive collapse. Consequently, the catastrophic event of progressive collapse in multistorey structures can be alleviated through appropriate designs and constructions adhering to the rules established in standardized regulations, as indicated by the literature examined in this research.

5.2 Recommendations

This research has elucidated the mechanisms of progressive collapse and its prevention in multistory buildings. In light of the findings presented in the review, the subsequent recommendations are proposed;

1. The design of multistorey buildings must adhere to criteria that account for unintentional load effects, which may result in the slow collapse of these structures.

2. While designing and constructing multistorey buildings, errors should be minimized to prevent the occurrence of progressive collapse.
3. Principal load bearing elements should be properly designed to enhance structural properties that will resist progressive collapse.
4. Prior to the construction of multistorey structures, it is advisable to conduct an evaluation for progressive collapse to evaluate the structural integrity.

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