Progressive Collapse Analysis of Tall Buildings Using the Alternate Path Method: A State-of-the-Art Review

Shamal Gopalrao Raut[1], Girish Joshi[2]

[1]PG Student, Department of Civil Engineering (Structural Engineering), G.H. Raisoni College of Engineering and Management, Pune, India
Email: *shamalraut001[at]gmail.com*

[2] Professor, Department of Civil Engineering (Structural Engineering), G.H. Raisoni College of Engineering and Management, Pune, India
Email: *girish.joshi[at]raisoni.net*

Abstract: ***Progressive collapse of tall buildings, characterized by the disproportionate spread of localized damage to the entire structural system, has emerged as a critical concern for structural engineers since the Ronan Point collapse of 1968 and the World Trade Center attacks of 2001. Among the principal design philosophies introduced by GSA (2003, 2016) and DoD UFC 4-023-03 (2009, 2016), the Alternate Path Method (APM) has gained pre-eminence due to its threat-independent character and its compatibility with both linear and nonlinear analysis frameworks. This review consolidates more than four decades of progressive collapse research, with a focused synthesis of contributions published between 2005 and 2024 on the application of APM to tall buildings, including reinforced concrete moment frames, steel moment frames, composite systems, outrigger-braced systems, diagrid structures, and tube-in-tube configurations. Linear static, nonlinear static, linear dynamic, and nonlinear dynamic procedures are critically compared in terms of accuracy, computational demand, and code applicability, with particular attention to the dynamic amplification factor, catenary action, Vierendeel action, and load redistribution mechanisms. The review further examines mitigation strategies including the use of shape memory alloys, fiber-reinforced polymers, steel bracing retrofits, and outrigger-belt truss arrangements. Knowledge gaps are identified concerning the influence of soil-structure interaction, multi-column removal scenarios, blast-induced collapse, fire-induced progressive collapse, and the integration of machine learning with finite element simulations for rapid vulnerability assessment. The paper concludes with recommendations for future research aimed at performance-based progressive collapse design of tall buildings in seismically active regions.***

Keywords: Progressive collapse; Alternate path method; Tall buildings; Column removal; Catenary action; Dynamic amplification factor; GSA guidelines; DoD UFC 4-023-03; Nonlinear dynamic analysis; Disproportionate collapse

1. Introduction

Progressive collapse, also termed disproportionate collapse, is defined by ASCE/SEI 7-22 as the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large portion of it. The phenomenon first received international attention following the partial collapse of the 22-storey Ronan Point apartment building in London on 16 May 1968, which was triggered by a gas explosion on the 18th floor. Since then, several catastrophic events including the bombing of the Alfred P. Murrah Federal Building in Oklahoma City (1995), the collapse of the World Trade Center towers (2001), and the Plasco Building fire-induced collapse in Tehran (2017) have reinforced the need for explicit progressive collapse provisions in modern structural design codes.

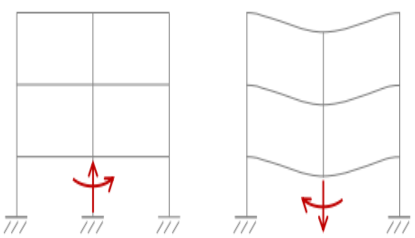

Figure 1: Stages of pulldown method

Tall structures are difficult to evaluate for progressive collapse because to lower-storey column gravity loads, P-Delta effects, and greater death and economic impact. After losing a principal load-carrying element, usually a column, the Alternate Path Method (APM) is the most widely used analytical procedure to mitigate disproportionate collapse.

2. Historical Background and Code Evolution

2.1 Notable progressive collapse incidents

Ronald Point's 1968 collapse introduced disproportionate collapse to engineering. A single load-bearing precast wall panel disintegrated, causing the 18th-story corner to fall. Since Griffiths, Pugsley, and Saunders (1968) researched, British regulations require five-story buildings to resist the loss of one load-bearing part. Half the Alfred P. Murrah Federal structure collapsed in 1995 due to blast-induced column loss via transfer girders. According to forensic studies by Corley et al. (1998), inadequate column detailing and interrupted reinforcing produced the extreme reactivity. FEMA 403 (2002) and NIST NCSTAR 1 (2005) recommended progressive collapse procedures for federal buildings following the 2001 World Trade Center tower fall due to fire-induced steel softening when the aeroplane impacted. The Tehran Plasco Building collapse (2017) and Surfside, Florida's Champlain Towers South disaster (2021) showed fire- and corrosion-induced tall building collapse.

2.2. Evolution of progressive collapse design codes

First introduced in the British Code of Practice CP 110 (1972), progressive collapse regulations mandated tying force for constructions above five floors. Structure integrity was required by ASCE 7-95 but not analytical methodologies. New and existing government buildings have to use the Alternate Path Method under the initial GSA guidelines (GSA 2003). The Department of Defence then adopted UFC 4-023-03 in 2005, revised in 2009 and 2016, which included TF, AP, and ELR design methods. In 2016, the GSA added plastic rotation limit acceptance criteria that matched ASCE 41 nonlinear analysis. For Class 2B and Class 3 buildings, Eurocode 1 Part 1-7 (2006) requires notional column removal or critical element design's and DoD recommendations generate comparable demand-to-capacity ratios for conventional steel and RC frames, however DoD UFC's dynamic amplification factor (DAF) changes between linear and nonlinear processes, according to Marjanishvili and Agnew (2006) and Kim and Kim (2009).

3. The Alternate Path Method: Principles and Procedures

3.1 Conceptual basis

The threat-independent varied Path method (APM) removes a column and examines the surviving structure's gravity load transmission via distinct load channels. This technique does not need column loss cause without sufficient hazard assessment for accidental and purposeful mishaps. Flexural beams above the removed column, Vierendeel frame system, and catenary or membrane action during major deformations impact the bridging structure's reaction. Axial restraint and ductility in beam-column connections seldom allow catenary motion in reinforced concrete frames without continuous bottom reinforcement.

3.2 Analysis procedures

3.2.1 Linear Static (LS) procedure

LS streamlines analysis. Amplified gravity loads (DL + 0.25 LL) and Dynamic Amplification Factor test the bridge construction. GSA (2003) developed a constant DAF of 2.0 using the energy balance of an undamped single-degree-of-freedom system losing support. By replacing the constant DAF with an experimental expression based on the bridging beam's plastic rotation acceptance requirements, the 2016 revision and DoD UFC 4-023-03 (2016) raised DAFs from 1.2 to 2.0 Because it cannot capture material and geometric nonlinearities, the LS approach is confined to typical constructions under 10 storeys.

3.2.2 Nonlinear Static (NS) procedure

Like pushover analysis, the NS approach slowly applies gravity loads to the damaged structure while monitoring plastic hinges, catenary action, and critical section demand-to-capacity ratios. DAF visits loaded bays near deleted column. For systems with significant nonlinearity, NS is superior than LS but cannot capture column breaking inertia and damping. NS peak displacement estimations in tall steel moment frames may underestimate dynamic response by 20–35%, according to Tsai & Lin (2008) and Kim and Yu (2012).

3.2.3 Linear Dynamic (LD) procedure

Once the column is eliminated instantaneously in the LD technique, direct integration time-history analysis analyses the structure as a linear elastic system. Inertial effects are captured but material nonlinearity, plastic hinge growth, and catenary motion are ignored. Research tests nonlinear results against baseline elastic responses using LD, although design seldom does.

3.2.4 Nonlinear Dynamic (ND) procedure

ND analysis is the most extensive and accurate of the four techniques. The column is removed in less than a tenth of the bridge beam's natural period, and the structure is analyzed utilizing geometric and material nonlinearity-aware direct integration of the equations of motion. Common software platforms include LS-DYNA, ABAQUS/Explicit, ANSYS, OpenSees, SAP2000 (with nonlinear link sections), and ETABS. ND analysis is accurate but computationally expensive for tall structures with hundreds of degrees of freedom and requires careful damping model, integration time step, and column removal duration selection. According to Sasani and Sagiroglu (2008) field testing on the Hotel San Diego, ND simulations may forecast peak vertical displacements within 15% of observed values given accurate material models and connection behavior.

Table 2: Comparison of the four APM analysis procedures

Procedure	Material Behaviour	Inertial Effects	Computational Cost	Recommended Use	Reported Accuracy
Linear Static	Linear elastic	Indirect (via DAF)	Very low	Regular low-rise (≤10 storeys)	Conservative; ±30%
Nonlinear Static	Nonlinear	Indirect (via DAF)	Moderate	Mid-rise frames	Moderate; ±20%
Linear Dynamic	Linear elastic	Direct (time history)	High	Benchmark / research	Limited; elastic only
Nonlinear Dynamic	Nonlinear	Direct (time history)	Very high	Tall buildings, irregular structures	High; ±10–15%

4. Key Parameters Influencing Progressive Collapse Response

4.1 Building height and number of storeys

Tall buildings gradually fall following column loss depending on the column's location. Because the gravity load tributary area is largest and alternative channels are geometrically limited, removing a lower-storey corner or perimeter column generally has the worst response. Kim and Park (2008) found that peak vertical displacements at the column removal location increased by 40% as height increased from 5 to 20 storeys, but demand-to-capacity ratios at the upper floors decreased due to the longer load redistribution path. Khandelwal and El-Tawil (2011) found that catenary action generated 35 to 50% of load redistribution capacity in tall buildings and less than 20% in low-rise frames in nonlinear dynamic analyzes of 10 and 20 storey braced frames.

4.2 Column removal location

GSA and DoD recommend corner column, exterior penultimate, interior, and column next to a re-entrant corner for column removal. Comparative investigations show that corner column removal causes the most displacement and rotation, whereas interior column removal causes the most beam axial demands owing to membrane action mobilized in two orthogonal directions. Tsai (2010) found that corner column removal caused peak vertical displacements 1.8 times more than interior column removal in a 12-storey steel moment frame, despite lower tributary loads. Helmy, Salem, and Mourad (2012) discovered that bay aspect ratio and bottom reinforcement continuity affected corner versus interior column removal in RC moment frames.

4.3 Dynamic amplification factor (DAF)

To compensate for inertial effects in static analysis, the DAF boosts gravity on bays near the removed column. The energy balance of a linearly elastic, undamped single-degree-of-freedom oscillator gave GSA (2003)'s constant value of 2.0. For ductile materials, where the DAF approaches 1.2 to 1.5 for large plastic rotations, Stevens et al. (2008), Marchand et al. (2009), and Liu (2013) proved that this number is too conservative. The improved DAF lowers the demand-to-capacity ratio in nonlinear analysis by 15–25% compared to 2.0, according to Naji and Khodaverdi (2013) sensitivity testing

4.4 Catenary and membrane action

Catenary action in beams and membrane action in slabs are second-order load-resisting mechanisms that are mobilized only after substantial deformations. In RC structures, the development of catenary action requires continuous bottom reinforcement passing through the column joint, adequate development length, and connection ductility. Yi et al. (2008) conducted full-scale tests on a four-bay, three-storey RC frame and observed that catenary action increased the load-carrying capacity by approximately 60 per cent beyond the flexural capacity of the bridging beam. Similar conclusions were reached by Sadek, Main, and Lew (2011) for steel moment frames with bolted-welded connections.

5. Progressive Collapse Performance of Tall Building Structural Systems

5.1 Reinforced concrete moment frames

The most researched structural system in progressive collapse is RC moment-resisting frames. In their landmark field test on the Hotel San Diego, Sasani and Sagiroglu (2008) showed that a six-story RC frame without progressive collapse provisions could redistribute loads after the explosive removal of a perimeter column with peak vertical displacements of 15 mm. In a parametric study of 10-story RC moment frames, Bao, Lew, and Kunnath (2014) found that ACI 318-11 special moment frame detailing allows progressive collapse under interior column removal, while gravity-only moment frames fail. Recently, Pham and Tan (2017, 2019) found that slab membrane action may contribute up to 70% of load redistribution capacity in flat-plate systems.

5.2 Steel moment frames

The partial collapse of WTC 7 prompted substantial research on steel moment frames. Khandelwal, El-Tawil, and Sadek (2009) revealed that seismically built special moment frames (SMF) had better progressive collapse resistance than SCBF during column removal owing to improved rotational ductility at the connections. Sadek et al. (2011) found that RBS connections, built for seismic ductility, offer appropriate rotational capacity for catenary action under column loss. Fu (2009, 2010) used ABAQUS/Explicit to study tall steel structures above twenty storeys and found a three-stage response: elastic, flexural-yielding, and catenary.

5.3 Composite and outrigger-braced systems

Composite steel-concrete systems combine reinforced concrete's bulk with structural steel's flexibility. Kim, Lee, and Hong (2010) discovered that composite slabs with shear studs improve membrane action and reduce peak vertical displacements by 25–40% over steel frames. Outriggers shift gravity loads from the center core to the surrounding columns, allowing tall structures exceeding forty storeys to bridge even when a perimeter mega-column is lost, according to Kim and Kim (2014) and Lin et al. (2017). With Vierendeeling numerous perimeter columns, the belt truss enhances load distribution.

5.4 Diagrid and tube-in-tube systems

Redundant triangulated perimeter diagrid constructions resist progressive collapse. Kim and Lee (2010) and Mashhadiali and Kheyroddin (2014) found that 60-storey diagrid towers reduce vertical demand-to-capacity ratios by 40% compared to moment frames during multiple column removal. Diagiris' apparent resilience depends on the failure circumstances. Losing two adjacent nodes might cause localized buckling and rapid collapse spread. Due to their redundant structure, tube-in-tube systems, where the inner core and outer perimeter tube share the gravity load, have good progressive collapse behavior.

6. Mitigation and Retrofit Strategies

6.1 Tying force and continuity reinforcement

The Tying Force (TF) method prescribed by DoD UFC 4-023-03 requires that horizontal and vertical ties be continuous throughout the structure, with prescribed tensile capacities computed from the gravity load combination. The method is straightforward to implement and is particularly effective in RC structures where continuous bottom reinforcement enables catenary action. Studies by Stinger and Orton (2012) and Yu and Tan (2013) have demonstrated that the inclusion of continuous bottom reinforcement in RC beams increases the catenary capacity by 60 to 100 per cent.

6.2 Fiber-reinforced polymer (FRP) retrofit

Externally bonded FRP laminates have been investigated as a retrofit strategy for existing buildings deficient in progressive collapse resistance. Orton, Jirsa, Bayrak (2009) tested half-scale RC beam-column subassemblages strengthened with carbon FRP and reported a 50 per cent increase in catenary capacity compared with control specimens. Qian and Li (2020) extended this work to 12-storey RC moment frames using nonlinear dynamic analysis and reported that FRP retrofits at the bottom of beams increased the load redistribution capacity by approximately 80 per cent under interior column removal.

6.3 Shape memory alloys (SMA)

Shape memory alloys, particularly Ni-Ti (Nitinol), Cu-based, and Fe-based alloys, exhibit superelastic behavior with recoverable strains of up to 8 per cent and energy dissipation through hysteresis. Their application in beam-column connections, link beams, and bracing elements has been investigated as a means of providing both seismic and progressive collapse resistance. Studies by Hu, Choi, and Park (2013) and DesRoches et al. (2014) have demonstrated that SMA-based connections recover most of their pre-collapse deformations after column loss, enabling rapid post-event reoccupancy. The implementation of SMA elements in commercial finite element software typically employs parallel link element assemblies with Pivot hysteresis models calibrated to experimental cyclic data.

6.4 Steel bracing and outrigger retrofits

Conventional steel bracing systems, including concentric and eccentric configurations, have been used as progressive collapse retrofits, particularly in tall buildings. Kim and Hong (2011) evaluated the retrofit of a 15-storey steel moment frame with X-bracing at selected bays and reported that the introduction of bracing reduced peak vertical displacements by 40 per cent and eliminated plastic hinging in adjacent beams. The use of buckling-restrained braces (BRB) has been proposed by Hoffman and Fahnestock (2011) as an alternative that combines high energy dissipation with stable post-yield behavior, although their cost and detailing requirements limit their adoption in conventional buildings.

7. Recent Advances and Emerging Trends

7.1 Machine learning for rapid vulnerability assessment

The high computational cost of nonlinear dynamic analysis has motivated the development of surrogate models based on artificial neural networks (ANN), support vector machines (SVM), random forests, and gradient boosting. Zhu et al. (2021) trained an ANN on 1,200 nonlinear dynamic simulations of steel moment frames and demonstrated that the network predicted peak vertical displacements within 8 per cent of the finite element ground truth, with a computational speed-up of approximately 10,000 times. Zhang et al. (2024) extended this approach to 70-storey diagrid towers using OpenSees-generated training data and reported that hybrid CNN-LSTM models can capture both spatial and temporal aspects of collapse propagation. The integration of machine learning with traditional finite element analysis offers significant promise for design office applications, enabling rapid screening of column removal scenarios during the preliminary design phase.

7.2 Multi-hazard and multi-column removal scenarios

In unintentional events like car crash or localised explosion, conventional APM analysis considers a single column loss. However, terrorist strikes and big fires may destroy numerous columns. Multi-column removal frameworks based on energy-based pushover analysis by Stylianidis, Nethercot, and Izzuddin (2016) and Tian, Li, and Yang (2019) provide fast evaluation of complicated damage scenarios without repeated nonlinear dynamic studies. Kodur and Naser (2020) on fire-induced collapse and Yu, Nethercot, and Izzuddin (2017) on seismic-progressive collapse demands are noteworthy contributions to multi-hazard framework research to integrate progressive collapse with seismic, blast, and fire impacts.

7.3 Performance-based progressive collapse design

PB-PCD applies performance-based seismic engineering to progressive collapse limit states. Marchand, McKay, and Stevens (2009) and Ellingwood et al. (2009) suggested a probabilistic framework to quantify structural reliability by convolution hazard, response, and consequence distributions. Petrone, Shan, and Kunnath (2016) and Yu et al. (2022) created column removal fragility curves for tall building risk-informed decision-making. Design codes will likely adopt PB-PCD in the next code cycle, especially in seismically active and progressive collapse regions.

8. Critical Research Gaps

- Soil–structure interaction is commonly neglected in APM studies, despite foundation flexibility significantly influencing dynamic amplification and column-loss response in tall buildings on soft soils.
- Existing design codes primarily consider single-column removal, while realistic multi-column loss scenarios caused by explosions or terrorist attacks remain insufficiently investigated.
- The combined effects of progressive collapse and seismic demands at different performance levels are not clearly understood for performance-based tall buildings.
- Fire-induced progressive collapse remains inadequately addressed in major design codes, and available research is fragmented.
- Progressive collapse behaviour of outrigger, diagrid, and hybrid structural systems requires further investigation and system-specific design provisions.

9. Conclusions and Recommendations for Future Research

- The Alternate Path Method remains the most widely adopted analytical framework for progressive collapse assessment due to its threat-independent character and its compatibility with both linear and nonlinear procedures.
- Among the four procedures, nonlinear dynamic analysis provides the most accurate prediction of peak displacements and internal forces, with reported errors

Paper ID: SR26808194807 DOI: https://dx.doi.org/10.21275/SR26808194807

within 10 to 15 per cent of full-scale field measurements, but at considerable computational expense.

- The dynamic amplification factor prescribed in early GSA (2003) guidelines was overly conservative for ductile structures; the displacement-dependent DAF formulations introduced in GSA (2016) and DoD UFC (2016) yield more realistic demand-to-capacity ratios.
- Tall buildings with outrigger-belt systems, diagrid configurations, and tube-in-tube arrangements exhibit superior progressive collapse performance due to their inherent redundancy, although this advantage is conditional on the specific failure scenario.
- FRP retrofits, SMA-based connections, and steel bracing arrangements have all been demonstrated to provide significant enhancement of progressive collapse resistance, with capacity increases of 40 to 100 per cent reported in the literature.

References

[1] American Concrete Institute. (2019). Building code requirements for structural concrete (ACI 318-19) and commentary. Farmington Hills, MI: ACI.

[2] American Society of Civil Engineers. (2022). Minimum design loads and associated criteria for buildings and other structures (ASCE/SEI 7-22). Reston, VA: ASCE.

[3] Bao, Y., Lew, H. S., & Kunnath, S. K. (2014). Modeling of reinforced concrete assemblies under column-removal scenario. Journal of Structural Engineering, ASCE, 140(1), 04013026.

[4] Corley, W. G., Sr., Mlakar, P. F., Sozen, M. A., & Thornton, C. H. (1998). The Oklahoma City bombing: Summary and recommendations for multi hazard mitigation. Journal of Performance of Constructed Facilities, ASCE, 12(3), 100-112.

[5] Department of Defense. (2016). Design of buildings to resist progressive collapse (UFC 4-023-03). Washington, DC: U.S. Department of Defense.

[6] DesRoches, R., McCormick, J., & Delemont, M. (2014). Cyclic properties of superelastic shape memory alloy wires and bars. Journal of Structural Engineering, ASCE, 140(2), 04013027.

[7] Ellingwood, B. R., Smilowitz, R., Dusenberry, D. O., Duthinh, D., Lew, H. S., & Carino, N. J. (2007). Best practices for reducing the potential for progressive collapse in buildings (NISTIR 7396). Gaithersburg, MD: NIST.

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

[9] Federal Emergency Management Agency. (2002). World Trade Center building performance study (FEMA 403). Washington, DC: FEMA.

[10] Fu, F. (2009). Progressive collapse analysis of high-rise building with 3-D finite element modeling method. Journal of Constructional Steel Research, 65(6), 1269-1278.

[11] Fu, F. (2010). 3-D nonlinear dynamic progressive collapse analysis of multi-storey steel composite frame buildings: Parametric study. Engineering Structures, 32(12), 3974-3980.

[12] General Services Administration. (2016). Alternate path analysis & design guidelines for progressive collapse resistance. Washington, DC: U.S. General Services Administration.

[13] Helmy, H., Salem, H., & Mourad, S. (2012). Progressive collapse assessment of framed reinforced concrete structures according to UFC guidelines for alternative path method. Engineering Structures, 42, 127-141.

[14] Hoffman, S. T., & Fahnestock, L. A. (2011). Behavior of multi-story steel buildings under dynamic column loss scenarios. Steel and Composite Structures, 11(2), 149-168.

[15] Hu, J. W., Choi, E., & Park, J. (2013). Investigating the smart tendon design and seismic performance of SMA-based steel structures. Smart Materials and Structures, 22(6), 065008.

[16] Indian Standards. (2017). Criteria for structural safety of tall concrete buildings (IS 16700:2017). New Delhi: Bureau of Indian Standards.

[17] Khandelwal, K., & El-Tawil, S. (2011). Pushdown resistance as a measure of robustness in progressive collapse analysis. Engineering Structures, 33(9), 2653-2661.

[18] Khandelwal, K., El-Tawil, S., & Sadek, F. (2009). Progressive collapse analysis of seismically designed steel braced frames. Journal of Constructional Steel Research, 65(3), 699-708.

[19] Kim, J., & Hong, S. (2011). Progressive collapse performance of irregular buildings. The Structural Design of Tall and Special Buildings, 20(6), 721-734.

[20] Kim, J., & Kim, T. (2009). Assessment of progressive collapse-resisting capacity of steel moment frames. Journal of Constructional Steel Research, 65(1), 169-179.

[21] Kim, J., & Lee, Y. (2010). Progressive collapse resisting capacity of tube-type structures. The Structural Design of Tall and Special Buildings, 19(7), 761-777.

[22] Kim, J., & Park, J. (2008). Design of steel moment frames considering progressive collapse. Steel and Composite Structures, 8(1), 85-98.

[23] Kim, J., & Yu, J. (2012). Analysis of reinforced concrete frames subjected to column loss. Magazine of Concrete Research, 64(1), 21-33.

[24] Kim, J., Lee, Y., & Hong, S. (2010). Effect of composite slab action on progressive collapse resistance of steel moment frame buildings. Journal of Constructional Steel Research, 66(11), 1411-1418.

[25] Kim, T., & Kim, J. (2014). Progressive collapse-resisting capacity of steel moment frames considering panel zone deformation. Advances in Structural Engineering, 17(11), 1607-1624.