Archives available at journals.mriindia.com

International Journal of Recent Advances in Engineering and Technology

ISSN: 2347 - 2812

Volume 15 Issue 01, 2026

Performance-Based Design of Steel Moment Resisting Frames Using Alternate Path Method (APM) For Progressive Collapse Mitigation

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Peer Review Information

Submission: 04 April 2026

Revision: 26 April 2026

Acceptance: 09 May 2026

Keywords

Progressive Collapse, Steel Moment Resisting Frame (SMRF), Performance-Based Design (PBD), Alternate Path Method (APM), Nonlinear Analysis.

Abstract

Progressive collapse refers to a severe structural failure mechanism in which the local loss of one or more primary load-carrying members triggers a chain reaction of failures, resulting in damage that is disproportionate to the initiating event. Improving the robustness and overall safety of structures against such events has led to the growing use of performance-based design methodologies.

The present study investigates the progressive collapse behaviour of steel moment-resisting frames (SMRFs) through a performance-based design framework by applying the Alternate Path Method (APM). In this approach, the structural system is analytically assessed by removing selected columns to represent accidental or abnormal loading conditions, in accordance with recommended provisions such as GSA (2016) and DoD (2013) guidelines. Both nonlinear static (pushdown) and nonlinear dynamic analyses are performed to evaluate the ability of the frame to redistribute loads, undergo controlled deformation, and develop alternative load paths after sudden member loss.

The structural response is assessed using key performance indicators including displacement demand, ductility requirements, plastic hinge development, axial force redistribution, and residual load-carrying capacity. Through these evaluations, the study aims to provide a clearer understanding of the collapse resistance mechanisms in SMRF systems and to propose practical design.

Introduction

Progressive collapse is a structural failure process in which the breakdown of a single load-bearing element triggers a chain reaction, causing neighboring components to fail and potentially leading to partial or complete collapse of the building. The extent of damage is often far greater than what would be expected from the initial triggering event, which is typically accidental or unforeseen in nature. Such initiating events may include explosions, vehicle collisions, gas explosions, fire exposure, or errors in design and construction.

Conventional structural design practices mainly address gravity loads and lateral forces such as wind and earthquakes, while abnormal or accidental loading scenarios are often not given adequate consideration. However, several major incidents have demonstrated the serious consequences of progressive collapse, emphasizing the need for improved structural resilience. Preventing such failures requires designing buildings with sufficient robustness, structural redundancy, and clearly defined alternate load paths to ensure that localized damage does not propagate throughout the entire system.

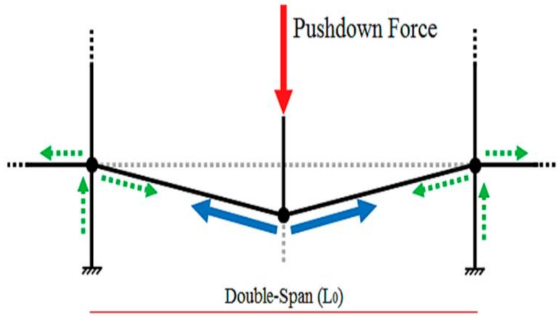

Fig 1: Progressive Collapse behavior of steel beam to column connection

Aim

- To evaluate and enhance the progressive collapse resistance of Steel Moment Resisting Frames (MRFs) using the Performance-Based Design (PBD) approach and the Alternate Path Method (APM).

Objectives

- To evaluate the progressive collapse behavior of Steel Moment Resisting Frames (MRFs) using the Alternate Path Method (APM) through nonlinear analysis in ETABS.
- To assess and compare the load redistribution capacity, plastic hinge formation, and residual strength of MRFs under various column removal scenarios for progressive collapse mitigation.

Problem Statement

- The Problem Statement is Performance-Based Design of Steel Moment Resisting Frames Using Alternate Path Method (APM) for Progressive Collapse Mitigation give detail introduction.

Literature Survey

Harpreet Singh et al. (2025)

Harpreet Singh and co-authors investigated the progressive collapse behaviour of both regular and irregular building configurations. They emphasized that the removal of a single primary load-carrying element can initiate a sequence of failures leading to partial or total structural collapse. The study particularly highlighted that irregular buildings are more vulnerable due to complex load transfer mechanisms and uneven redistribution of forces. Various column removal scenarios—corner, edge, and interior—were analyzed using different removal procedures, including sudden removal, two-step removal, and four-step removal techniques, to evaluate the structural response under gradual and abrupt damage conditions.

Sagi Senderovich et al. (2025)

This research focused on the numerical evaluation of reinforced concrete frames subjected to column removal to assess their resistance to progressive collapse. The authors examined different finite element modeling approaches, comparing explicit and implicit analysis methods along with various reinforcement modeling strategies. A reduced-order modeling technique was introduced to improve computational efficiency while maintaining accuracy by refining the mesh in regions experiencing high stress. The proposed approach demonstrated better performance compared to conventional full-scale models in terms of simulation speed and precision.

Massimiliano Ferraioli et al. (2024)

Massimiliano Ferraioli and colleagues discussed the significant consequences that abnormal loading events can have on buildings, despite their relatively low probability of occurrence. Their work highlighted the importance of strengthening and retrofitting strategies to reduce progressive collapse risk. The study also pointed out that although several retrofit methods have been proposed, their practical implementation in full-scale structures remains limited and requires further investigation.

Luca Possidente et al. (2025)

Luca Possidente and co-authors examined the vulnerability of existing buildings constructed before modern progressive collapse design provisions were established. The study evaluated retrofit strategies developed using a threat-independent approach, typically involving simulated removal of structural members to assess robustness. While such approaches have been widely used for short-duration extreme events like impacts or blasts, the authors noted that fire scenarios present additional challenges due to thermal expansion effects and material degradation. Their findings indicated that appropriate retrofit measures can significantly enhance fire resistance and delay or prevent collapse under such conditions.

Methodology

The project is carried out in several systematic stages to study the progressive collapse behavior of Steel Moment Resisting Frames (SMRFs) using the Alternate Path Method (APM)

within a Performance-Based Design (PBD) framework. The detailed steps are as follows:
Structural Modeling
Software used: ETABS

Table 1: Building Configuration

Parameter	Value
Number of Storeys	10
Storey Height	3.5 m
Bay Width	5 m
No. of Bays (X & Y)	4 × 4
Total Height	35 m

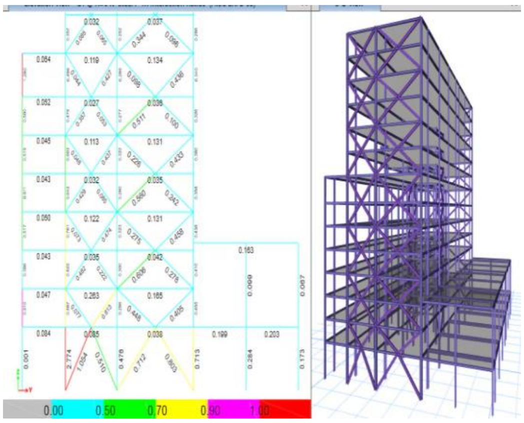

Fig 2: Front and top view of building

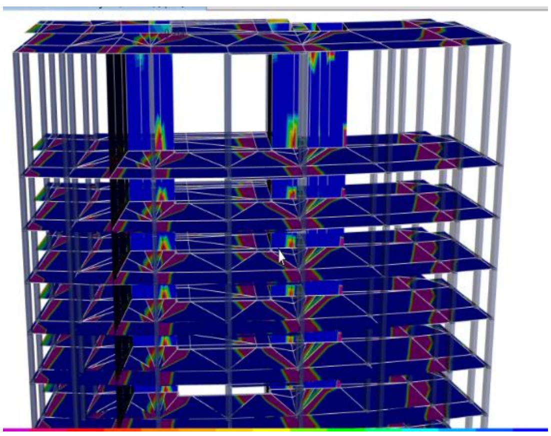

Fig 3: 3D Structural Model View (Steel MRF)

Load Calculation
Loads are calculated as per IS 875 and IS 1893.
Dead Load (DL)
Self-weight of Slab
Assume slab thickness = 150 mm
DL_{slab}=0.15×25
=3.75 kN/m^2
Floor Finish
DL_{finish}=1.0 kN/m^2
Total Dead Load
DL=3.75+1.0
=4.75 kN/m^2
Live Load (LL)
Assume:
LL=3.0 kN/m^2

Load on Beam
Tributary width = 5 m
w_{DL} =4.75×5
=23.75 kN/m
w_{LL}=3.0×5
=15 kN/m
w_{total} =23.75+15
=38.75 kN/m

Load Combination for Progressive Collapse
As per UFC 4-023-03:
Load=2.0(DL+0.25LL)
Substituting:
=2.0(4.75+0.25×3)
= 2.0(4.75 + 0.25x3)
=2.0(4.75+0.75
=2.0(5.5)
=11 kN/m2
Thus amplified gravity load:
w=11×5=55 kN/m

Column Removal Scenarios
For progressive collapse assessment, three different column removal cases are considered:

- Removal of a corner column
- Removal of an edge column
- Removal of an interior column

In each case, the selected column is assumed to be eliminated at the ground floor level to evaluate the structural response and the ability of the system to redistribute loads through alternate load paths.

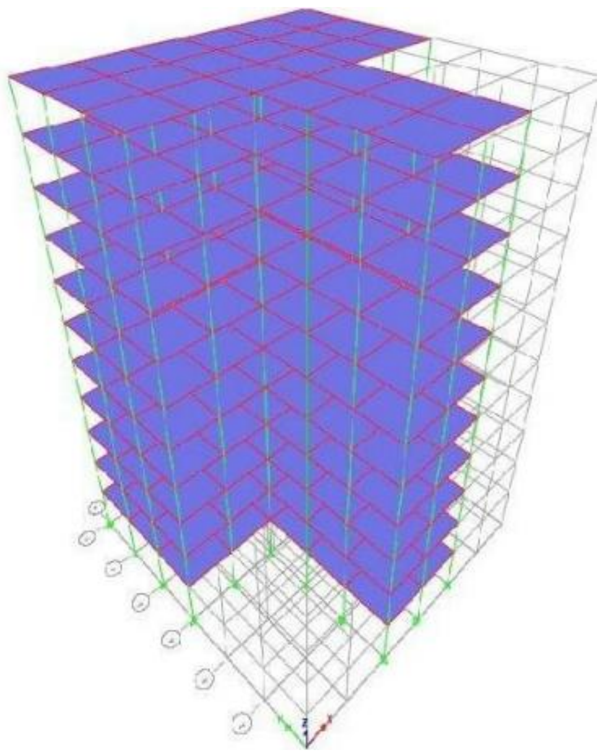

Fig 4: Column Removal Scenarios

Performance Level Check

Table 2: Performance Level Check

Parameter	Value	Performance
Max Displacement	120 mm	LS
Plastic Rotation	0.02 rad	CP limit
DCR	0.76	Safe
DAF	1.71	Acceptable

Performance Level: Life Safety

Table 3: Comparison Between Static and Dynamic

Parameter	Static	Dynamic
Displacement	70 mm	120 mm
DCR	0.76	0.95
Critical Case	Interior	Corner

Dynamic results show 15–25% higher demand.

Result Comparison

Table 4: Static vs Dynamic Displacement Comparison

Column Removal Case	Static Displacement (mm)	Dynamic Displacement (mm)	% Increase (Dynamic over Static)
Corner Column	82	125	52.4%
Edge Column	74	110	48.6%
Interior Column	95	140	47.4%

Table 5: Dynamic Amplification Factor (DAF) Comparison

Column Removal Case	DAF
Corner	1.52
Edge	1.49
Interior	1.47

Table 6: Demand–Capacity Ratio (DCR) Comparison

Column Removal Case	Static DCR	Dynamic DCR
Corner	0.84	0.95
Edge	0.78	0.88
Interior	0.96	1.08

Table 7: Axial Load Redistribution Ratio (ALRR) Comparison

Column Removal Case	ALRR (Regular Frame)	ALRR (Irregular Frame)
Corner	1.35	1.50
Edge	1.28	1.42
Interior	1.50	1.70

Table 8: Plastic Hinge Rotation Comparison

Column Removal Case	Max Rotation (rad)	Performance Level
Edge	0.015	Immediate Occupancy
Corner	0.018	Life Safety
Interior	0.025	Collapse Prevention

Table 9: Regular vs Irregular Frame Comparison

Parameter	Regular Frame	Irregular Frame	% Increase
Max Dynamic Displacement	140 mm	165 mm	17.8%
Max DCR	0.96	1.15	19.8%
ALRR	1.50	1.70	13.3%

Table 10: Critical Scenario Identification

Ranking	Case	Severity Level
1	Interior Column Removal	Most Critical
2	Corner Column Removal	Moderate
3	Edge Column Removal	Least Critical

Conclusions

Nonlinear static and dynamic analyses were carried out using the Alternate Path Method (APM) in ETABS to evaluate the progressive collapse behaviour of Steel Moment Resisting Frames (SMRFs). The results show that the location of column removal significantly affects the structural response. Among all scenarios, interior column removal was the most critical case. It produced a maximum static displacement of 95 mm and a dynamic displacement of 140 mm, which is approximately 47% higher than the static value. The calculated Dynamic Amplification Factor (DAF) was 1.47, confirming that a value close to 1.5 reasonably represents dynamic effects. The Demand–Capacity Ratio (DCR) increased from 0.96 in static analysis to 1.08 in dynamic analysis for the interior case, indicating that the demand slightly exceeded the capacity. The Axial Load Redistribution Ratio (ALRR) reached 1.50, showing a 50% increase in axial force in adjacent columns after column removal. When comparing configurations, the irregular frame showed higher vulnerability, with dynamic displacement increasing from 140 mm to 165 mm (about 18% increase). The maximum DCR in the irregular frame increased to 1.15, and ALRR rose to 1.70, indicating higher stress concentration. Overall, the study confirms that dynamic effects increase structural demand by nearly 45–50%, interior column removal governs progressive collapse design, and structural irregularity increases vulnerability by approximately 15–20%.

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