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

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Abstract

Progressive collapse is a catastrophic structural failure that occurs when the loss of one or more critical load-bearing elements leads to disproportionate damage or total collapse of a structure. To enhance structural robustness and safety, performance-based design approaches have been increasingly adopted. This study focuses on the performance-based design of steel moment-resisting frames (SMRFs) using the Alternate Path Method (APM) to evaluate and mitigate the risk of progressive collapse. The research involves modeling steel frame structures subjected to sudden column removal scenarios to simulate accidental load cases as per guidelines from GSA (2016) and DoD (2013). Nonlinear static and dynamic analyses are conducted to assess load redistribution, deformation capacity, and energy absorption mechanisms within the frame. The results are evaluated based on performance criteria such as ductility demand, plastic hinge formation, and residual strength. The findings are expected to contribute to developing practical design recommendations for improving the robustness and resilience of steel moment-resisting frames under accidental loading conditions.

INTRODUCTION

Progressive collapse is a failure mechanism where the local failure of one structural component leads to the sequential failure of adjoining elements, resulting in partial or total collapse of the structure.
Such collapse is disproportionate to the initial cause, which may be accidental or unexpected.
Common initiating events include explosions, vehicle impacts, gas leaks, fire, or design/construction errors.

Need for Progressive Collapse Mitigation

- Modern design codes primarily focus on gravity and lateral loads (wind, seismic), often neglecting accidental or abnormal load cases.
- Real-world incidents (e.g., the 1968 Ronan Point collapse, 1995 Oklahoma City bombing, and 2001 World Trade Center attacks) highlighted the importance of designing structures capable of preventing progressive collapse.
- Mitigation requires robustness, redundancy, and alternate load paths in structural systems.
- Steel MRFs are widely used in multi-storey and high-rise buildings due to:
- High ductility and energy dissipation capacity
- Redundant load paths
- Good seismic performance
- However, under column loss or local beam to column connection

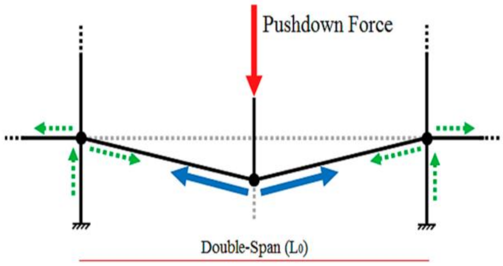

Fig. 1 Progressive Collapse behavior of steel

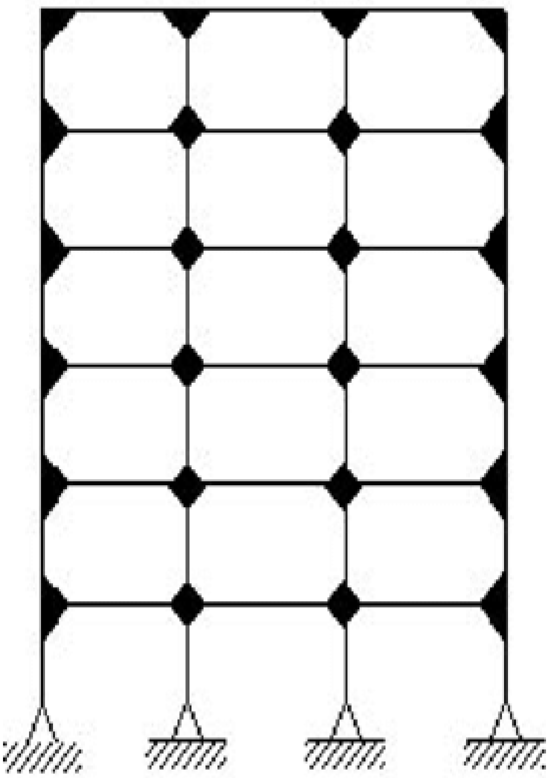

Fig. 2 Steel Moment Resisting Frames
Scope of the Study

Analyze Steel Moment Resisting Frames (MRFs) using ETABS or SAP2000 software.
Model different column removal scenarios (e.g., exterior, corner, and interior columns).
Perform nonlinear static/dynamic analysis following APM guidelines.
Evaluate parameters such as:
Vertical displacement
Hinge pattern and plastic rotation
Energy absorption and residual capacity
Propose design improvements to enhance progressive collapse resistance.

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

1. To evaluate the progressive collapse behavior of Steel Moment Resisting Frames (MRFs) using the Alternate Path Method (APM) through nonlinear analysis in ETABS.
2. 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.

LITERATURE REVIEW

Harpreet Singhetal (2025)

Progressive collapse represents a crucial structural phenomena in which the loss of a single load-carrying member sets off a chain reaction that results in partial or total breakdown of the structure. The likelihood of gradual collapse is particularly significant in irregular buildings, that feature more complicated load pathways and uncertain redistribution mechanisms. The current work addresses this issue by examining the gradual collapse performance of regular as well as irregular models under several column elimination scenarios, namely corner, edge, and interior, with three elimination methods: abrupt elimination, 2-step elimination, and 4-step elimination. This study examines the impact of structural regularity as well as plan irregularity on key factors like vertical displacement time history, chord rotation, Demand-Capacity Ratios (DCR) in columns as well as beams, and Axial Load Redistribution Ratio (ALRR) across two structure heights (5-storey as well as 10-storey), providing a thorough understanding of how structural design as well as column elimination techniques affect progressive collapse hazards.
The findings show that the corner column elimination case has the highest peak response across all models, with a 10–50 % rise in maximum displacement when compared to edge column elimination situations. In contrast, as plan irregularity grew in models, especially IM-2 and IM-5, the greatest responses occurred in the edge column elimination situation under abrupt column deletion events. Furthermore, DCR and ALRR outcomes demonstrated that in the event of gradually column elimination instances, these values were reduced by 5–10 %, indicating that the structure has a longer period to redistribute forces amongst other neighboring components. The results emphasize the significance of structural regularity and the necessity for strong design considerations to improve stability, especially in high-rise & irregular structures, and especially under seismic or deteriorating situations.

Sagi Senderovichetal (2025)
This study presents a comprehensive numerical investigation of reinforced concrete (RC) frames subjected to column removal, with a focus on structural robustness and resistance to progressive collapse. It reviews existing modeling approaches, evaluating the strengths and limitations of both explicit and implicit finite element analyses, as well as various strategies for modeling concrete and steel reinforcement. A novel reduced-order model (ROM) is proposed, which enhances simulation efficiency and accuracy by employing strategically refined meshes in regions of high stress concentration, outperforming conventional full-order models. Utilizing Abaqus, a series of comparative parametric studies was conducted to evaluate different reinforcement element types, mesh configurations, and overall model performance in terms of error and computational time. The results demonstrate that the proposed ROM provides higher efficiency and accuracy in the simulation of compressive and catenary structural behavior under extreme loading conditions. Furthermore, modeling steel reinforcement with truss elements, rather than beam elements, demonstrated superior computational efficiency, making them more suitable for large-scale progressive collapse simulations. These findings offer valuable insights for optimizing progressive collapse modeling and provide a practical framework for designing resilient RC structures in high-risk environments.

Massimiliano Ferraiolietal (2024)
Despite their low probability of occurrence, the consequences of abnormal loads may be very important, both in economic terms and in terms of human lives. This has stimulated the development of strengthening and retrofitting techniques to mitigate the risk of progressive collapse of buildings. However, their application to real-scale buildings is still lacking. This paper describes the progressive collapse analysis and retrofit of a steel-reinforced concrete hospital building. The progressive collapse performance under different column removal scenarios is investigated using both nonlinear static and dynamic analyses. A two-step pushdown analysis procedure is developed to estimate the dynamic amplification factor (DIF) to partially compensate for the dynamic effects. The results have revealed the vulnerability of the building due to the low tensile axial resistance of the beam- to column connections. Both the hypothesis of DIF = 2 and the almost inversely proportional relationship between DIF and vertical deflection have proven to be ineffective due to the catenary effect. A retrofit solution is proposed based on an outrigger-belt truss system on the rooftop level. The results show the effectiveness of the retrofit strategy. The displacement dynamic response of the retrofitted structure is significantly reduced if compared to the original structure since it goes from about 20 cm to less than 1 cm. However, the tensile strength of column to-column connections of the top three floors is inadequate and should be increased. To this aim, a strengthening intervention is developed to increase the tensile strength from 565 kN to 965 kN, thus allowing the tensile axial forces caused by the column removed to be resisted.

Luca Possidenteetal (2025)
A large share of the existing building stock was built before the implementation of design standards against progressive collapse and is in need for retrofitting. Retrofit measures are typically designed with a threat independent approach, involving the removal of one or more structural elements. This approach has been widely applied to deal with events such as impacts or blasts (short-duration events), but may not be adequate for fire scenarios (long-duration events) due to peculiar phenomena such as restrained thermal expansion and degradation of mechanical properties. This is particularly relevant for steel structures, which are sensitive to thermal attack and are typically designed as low-redundant systems, and used in large industrial or strategic buildings. This paper investigates the fire response of a 9-storey steel moment-resisting frame before and after progressive collapse retrofitting. Three retrofit measures designed considering the removal of the central ground storey column are investigated, including a bracing system, a roof-truss, and the concrete encasement of critical columns. Parametric fires, different compartment scenarios, and various loading levels are considered. The retrofit measures are shown to improve the fire response of the structure by preventing or delaying collapse. Finally, the effectiveness and suitability of the measures in different circumstances are discussed.

Luca Possidenteetal (2024)
Progressive or disproportionate collapse of structures may have severe socio-economic consequences. Aiming at buildings that can withstand such events, one solution is to prevent or minimize the propagation of damage that may lead to progressive collapse by means of robust design strategies. As a typical

approach to model progressive collapse and assess robustness, the Alternate Path Method (APM) allows for static analyses, in which the dynamic effects induced by a sudden column loss are taken into account by amplifying loads through a Dynamic Increase Factor. Current recommendations for Dynamic Increase Factors to be used within non-linear static analyses have mainly considered beam-type collapse, overlooking other failure mechanisms, e.g., column buckling. The present paper investigates the dynamic effects of steel structures subjected to progressive collapse when buckling of columns is relevant. Five low- to high-rise case study building structures are considered together with three different column loss scenarios. A numerical procedure is introduced to evaluate the Dynamic Increase Factors considering two different Engineering Demand Parameters (EDPs), suited for describing beam- and column-type mechanisms, respectively. As Dynamic Increase Factors are typically assessed by increasing the loads on all the spans (DIF), a procedure was proposed for deriving factors that apply only on the spans above the removal (DIF*), consistently with UFC guidelines. The obtained DIF and DIF* are compared with the current literature and with values recommended in the UFC guidelines, highlighting the limits of current recommendations. Relevant considerations on the derived Dynamic Increase Factors and failure mechanisms involved are provided.

Research Gap

There is limited research on integrating the Performance-Based Design (PBD) approach with the Alternate Path Method (APM) to study the progressive collapse behavior of Steel Moment Resisting Frames (SMRFs). Most existing studies focus on regular structures, while the effect of plan and vertical irregularities on load redistribution and collapse resistance is not well explored. The dynamic effects caused by sudden column loss are often simplified, and the existing Dynamic Increase Factors (DIF) may not accurately represent real behavior. Moreover, there is a lack of detailed investigation on load redistribution mechanisms, such as axial load transfer and plastic hinge formation, especially under realistic multi-hazard conditions like seismic or fire events. Hence, a detailed study is needed to evaluate the progressive collapse performance of SMRFs using a performance-based approach under various column removal scenarios.

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:

Model Development

The first step involves developing a detailed 3D analytical model of a steel moment resisting frame in ETABS. The structure is modeled as a multi-storey frame system with defined geometric parameters such as the number of bays, storey height, and total height. Two types of models are considered:

- Regular structure – uniform grid and member arrangement.
- Irregular structure – includes plan irregularity (unequal bays or offsets) and/or vertical irregularity (varying storey heights or mass distribution).

All beams and columns are modeled as nonlinear frame elements, with material properties assigned as per IS 800:2007 for steel structures. The connections are assumed to be rigid to represent a true moment-resisting frame behavior.

Structural Design

Before performing progressive collapse analysis, the frame is designed under conventional loading conditions to ensure code compliance. The following steps are performed:

- Loads are assigned according to IS 875 (Part 1–5) for dead, live, and wind loads.
- Seismic loads are applied as per IS 1893 (Part 1):2016.
- Member sizes are optimized based on the design output to meet strength and serviceability requirements.
- The designed structure serves as the baseline model for progressive collapse simulations.

Identification of Column Removal Scenarios

Progressive collapse is initiated by the removal of critical load-carrying members. According to UFC 4-023-03 (2016) guidelines, three key locations are considered for column removal:

1. Corner column
2. Edge column
3. Interior column

Each column is removed one at a time to observe the ability of the structure to develop alternate load paths. This simulates accidental damage caused by abnormal loading events such as explosion, impact, or seismic failure.

CONCLUDING REMARK

- A literature survey has been carried out to understand the existing research and identify knowledge gaps.
- The aim and objectives of the study have been clearly defined.
- The problem statement has been formulated based on the findings from the literature review.
- The research methodology has been outlined to guide the investigation effectively.
- A detailed research plan has been prepared to structure the overall study process.

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