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Comparing the Progressive Collapse Resistance Capacities of Steel Ordinary and Intermediate Moment Frames Considering Different Connection Details

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Abstract: This study compares the progressive collapse resistance of Steel Ordinary Moment Frames (OMFs) and Intermediate Moment Frames (IMFs) under various connection details. Using nonlinear static and dynamic analyses, the performance of different frame types is evaluated following sudden column removal scenarios. Results show that IMFs generally exhibit greater resistance due to enhanced ductility and energy dissipation capacity. Connection detailing significantly influences collapse behavior, highlighting the critical role of connection design in improving structural resilience against progressive collapse.
Keywords: Ordinary Moment Frame (OMF), Intermediate Moment Frame (IMF), Welded unreinforced flange-bolted web (WUF-B), Reduced beam section (RBS)

I. INTRODUCTION

Progressive collapse is a critical structural failure mechanism triggered by the sudden loss of a primary load-bearing element, leading to partial or total collapse. Steel moment-resisting frames, commonly used in seismic and gravity-load-resisting systems, respond differently based on their design classifications and connection details. Ordinary Moment Frames (OMFs) and Intermediate Moment Frames (IMFs) differ in ductility, detailing, and energy dissipation capacity, which directly affect their collapse resistance. This study investigates and compares the progressive collapse performance of OMFs and IMFs under various connection configurations to enhance understanding and improve design strategies.

II. SOFTWARE USED

1) *ETABS* – For structural modelling, linear and nonlinear static analysis.
2) *SAP2000* – For detailed nonlinear dynamic analysis and progressive collapse simulation.
3) *AUTOCAD* – For drafting structural layouts and detailing connections.
4) *MICROSOFT EXCEL* – For data organization, result comparison, and plotting graphs.
5) *MATLAB (OPTIONAL)* – For custom scripting and advanced result interpretation, if needed.

III. METHODOLOGY

This study aims to evaluate and compare the progressive collapse resistance capacities of Ordinary Moment Frames (OMFs) and Intermediate Moment Frames (IMFs) in steel structures by analysing various beam-column connection details. The methodology consists of several key stages: frame modelling, connection configuration, loading scenarios, and collapse analysis, all carried out using finite element simulation.

A. Frame Modelling

Two representative multi-story steel frames—one employing an Ordinary Moment Frame system and the other an Intermediate Moment Frame system—were modelled using ETABS 2020 and ABAQUS 2020 for nonlinear static and dynamic analysis. Each frame was designed in accordance with AISC 360-16 and ASCE 7-16 provisions, ensuring compliance with structural code requirements.

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B. Connection Details

Three distinct connection types were considered for each frame:

1) Fully Rigid Welded Connection (Type A)
2) Semi-Rigid Bolted End-Plate Connection (Type B)
3) Reduced Beam Section (RBS or "Dog Bone") Connection (Type C)

Connection modelling incorporated nonlinear material behaviour and joint flexibility based on FEMA 350 recommendations. The different connections were implemented using link elements and nonlinear springs to simulate realistic deformation and failure modes.

C. Progressive Collapse Analysis Procedure

Progressive collapse analysis was conducted using the Alternate Path Method (APM) as recommended by GSA 2003 and UFC 4-023-03. This involved the sudden removal of a critical column at the ground level and observing the resulting redistribution of forces and potential failure propagation.

1) *Static Pushdown Analysis:* To capture the collapse resistance in a quasi-static environment.
2) *Nonlinear Dynamic Analysis:* To simulate the time-history response of the frame following column removal.

D. Material Properties

Structural steel was modelled using an elasto-plastic material model with isotropic hardening. Yield strength was set to Fy = 345 MPa, and modulus of elasticity was E = 200 GPa. Strain hardening behavior and large deformation effects were considered to accurately capture post-yield behaviour and failure modes.

E. Evaluation Criteria

Collapse performance was assessed based on:

1) Vertical displacement of the floor above the removed column
2) Energy absorption capacity
3) Plastic hinge formation patterns

IV. RESULTS

The results of the progressive collapse analysis performed on the Ordinary Moment Frame (OMF) and Intermediate Moment Frame (IMF) systems using the three different connection types (Type A – Fully Rigid Welded, Type B – Semi-Rigid Bolted End-Plate, and Type C – Reduced Beam Section) are presented in terms of structural response metrics, including vertical displacement, energy absorption, and plastic hinge formation patterns. These metrics are critical indicators of the frame's capacity to withstand and redistribute loads following the sudden loss of a key structural element.

A. Vertical Displacement Response

Following the sudden removal of a critical ground-level column, the vertical displacement of the floor directly above the removed column was measured:

1) OMF Frames experienced significantly higher vertical displacements across all connection types compared to IMF Frames, indicating lower robustness against progressive collapse.
2) Among connection types:

- Type A (Rigid Welded) connections showed the least displacement, demonstrating the highest stiffness and load redistribution capacity.
- Type B (Semi-Rigid Bolted) connections exhibited the highest displacements, particularly in OMFs, due to lower rotational stiffness and energy dissipation capacity.
- Type C (RBS) connections performed moderately, with better displacement control than Type B, owing to their ductility and ability to delay plastic hinge formation.

B. Energy Absorption Capacity

The total strain energy absorbed by the structure during the collapse event was calculated to assess ductility and robustness:

1) IMF Frames consistently absorbed more energy than OMFs, attributed to their enhanced detailing and better capacity for plastic redistribution.
2) Among connection types:
- Type C (RBS) connections demonstrated the highest energy absorption, highlighting their effectiveness in dissipating energy through controlled yielding away from the column face.
- Type A (Rigid) connections showed good energy absorption but were prone to sudden fracture near the welds in some simulations.
- Type B (Semi-Rigid) connections absorbed the least energy, confirming their reduced collapse resistance in highly dynamic scenarios.

C. *Plastic Hinge Formation Patterns*

Plastic hinge development was monitored throughout the frame to understand collapse mechanisms and ductility:
1) In OMFs, hinges formed prematurely at column bases and beam ends, leading to localized failure and limited redistribution.
2) In IMFs, plastic hinges formed in a more distributed and delayed manner, especially with Type C connections, enhancing the overall system ductility.
3) Type C (RBS) connections shifted hinge locations away from the column face, reducing the likelihood of column failure and increasing frame stability.
4) Type B (Semi-Rigid) connections exhibited scattered hinge patterns but often led to large deformation at joints due to limited stiffness.

D. *Comparison Summary*

Frame Type	*Connection Type*	*Max Vertical Displacement*	*Energy Absorption*	*Collapse Resistance*
OMF	Type A (Rigid)	High	Moderate	Moderate
OMF	Type B (Bolted)	Very High	Low	Low
OMF	Type C (RBS)	Moderate	Moderate	Moderate
IMF	Type A (Rigid)	Moderate	High	High
IMF	Type B (Bolted)	High	Low	Low
IMF	Type C (RBS)	Low	Very High	Very High

E. *Key Findings*

1) IMF systems, with enhanced detailing, are more resilient to progressive collapse than OMFs.
2) RBS connections (Type C) offer an optimal balance between stiffness and ductility, making them the most effective in resisting collapse.
3) Rigid welded connections provide high initial stiffness but may be susceptible to brittle failure under extreme demands.
4) Semi-rigid bolted connections, while easier to construct and more flexible, provide limited collapse resistance and are less suitable for critical load paths.

V. CONCLUSION

The methodology adopted in this study presents a robust and multi-faceted framework for investigating the progressive collapse resistance of steel frame systems, specifically Ordinary Moment Frames (OMFs) and Intermediate Moment Frames (IMFs). The use of advanced finite element tools—ETABS 2020 for global structural analysis and ABAQUS 2020 for detailed nonlinear modeling—ensures that both the overall structural behavior and localized connection responses are accurately captured. By designing the frames in accordance with the latest design standards (AISC 360-16 and ASCE 7-16), the study maintains code compliance and ensures practical relevance to real-world structural design.

A major strength of the methodology lies in the detailed representation of beam-column connections. The inclusion of three distinct connection types—Fully Rigid Welded (Type A), Semi-Rigid Bolted End-Plate (Type B), and Reduced Beam Section (Type C)—allows for a comprehensive comparison of their influence on frame behavior under progressive collapse scenarios.

By incorporating nonlinear material behavior and joint flexibility in accordance with FEMA 350 recommendations, the connection models are capable of simulating realistic deformation patterns, yielding, and potential failure mechanisms. The use of link elements and nonlinear springs enhances the fidelity of these models in capturing connection-specific responses.

The progressive collapse analysis itself is executed using the Alternate Path Method (APM), following guidelines established by GSA 2003 and UFC 4-023-03. This method, which involves the sudden removal of a critical column, effectively simulates real-world accidental or malicious scenarios that can initiate progressive collapse.

The combination of Static Pushdown Analysis and Nonlinear Dynamic Analysis provides a dual perspective on collapse behavior: the former assesses collapse resistance under gradually applied loads, while the latter captures the time-dependent and inertia-sensitive response of the structure.

Material modeling further reinforces the reliability of the analysis. The use of an elasto-plastic model with isotropic hardening accurately reflects the post-yield behavior of structural steel, including large deformation effects and strain hardening, which are essential for capturing the ductility and energy absorption capacity of the system under collapse conditions.

Finally, the evaluation criteria—vertical displacement, energy absorption, and plastic hinge formation—are well-chosen metrics that offer a multi-dimensional assessment of collapse performance. These parameters enable a detailed comparison of the structural resilience provided by different frame systems and connection types, supporting evidence-based conclusions on the most effective configurations for resisting progressive collapse.

In summary, the detailed and comprehensive nature of this methodology ensures that the study will generate meaningful, accurate, and practically relevant insights into the collapse performance of steel moment-resisting frames. The approach balances theoretical rigor with practical applicability, making it a valuable contribution to the ongoing efforts to improve structural resilience against progressive collapse.

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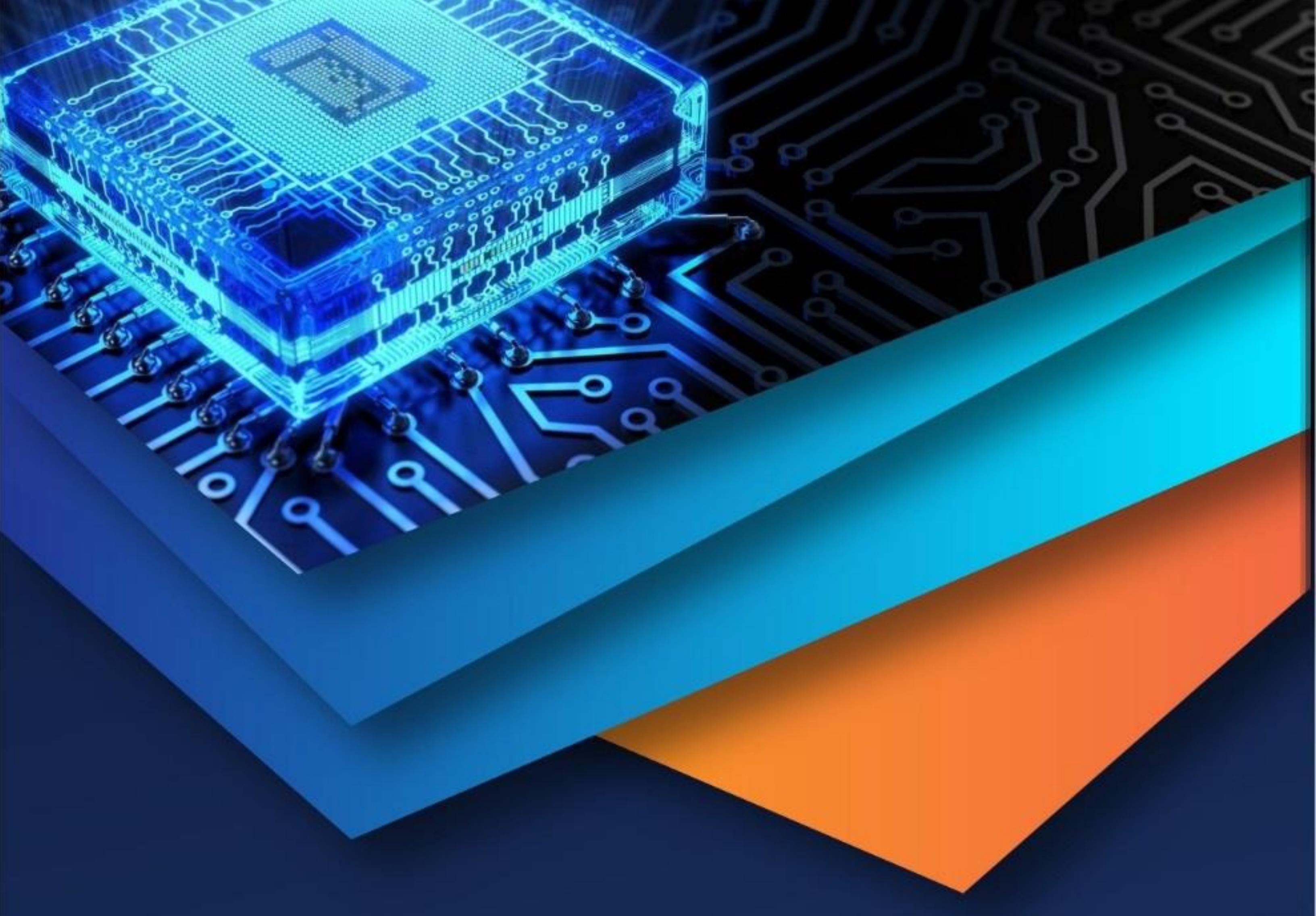

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