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Impact Of Connection Detailing on Progressive Collapse: Bolted Vs. Welded Joints in Steel Frames

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Abstract

The rapid growth of tall and slender buildings in contemporary architecture has increased the need for highly efficient lateral load-resisting systems. Steel diagrid structures have gained significant attention because of their structural efficiency, stiffness, and architectural adaptability.

This study investigates the optimization of steel diagrid systems to improve their performance under seismic and wind actions. A detailed parametric study is carried out by varying parameters such as diagrid inclination angle, member dimensions, and panel spacing. The influence of these parameters on key structural responses including lateral stiffness, inter-storey drift, and base shear is systematically evaluated.

Finite element modelling is used to develop accurate analytical models, and dynamic analysis procedures such as response spectrum analysis and time history analysis are performed to represent realistic loading scenarios. To determine the most efficient structural configuration, optimization approaches including genetic algorithms and multi-objective optimization techniques are applied. These methods aim to achieve an optimal balance between structural strength, stability, and material utilization.

The outcomes indicate that appropriately optimized diagrid systems can substantially enhance the lateral performance of tall buildings while reducing steel consumption and improving overall seismic resistance. The study offers practical guidance for structural engineers and designers seeking to develop sustainable, resilient, and high-performance tall building structures.

Introduction

Steel structures form a fundamental part of contemporary construction because of their high strength-to-weight ratio, ductile behavior, rapid construction capability, and design versatility. They are extensively adopted in tall buildings, industrial facilities, long-span bridges, and offshore structures. Despite these advantages, their performance under extreme or accidental actions such as blasts, vehicle collisions, fire exposure, or sudden loss of a column depends greatly on the design and detailing of beam column connections.

Connections are essential for ensuring continuity within the structural system. They transfer axial forces, shear forces, and bending moments between members and help maintain the stability of the overall frame. While structures are typically designed for gravity, wind, and seismic loads, their behavior during abnormal events relies heavily on the ability of connections to sustain large deformations and enable load redistribution. When a primary load-bearing element fails unexpectedly, the remaining structural components must develop alternative load paths to prevent widespread damage. This capacity for load redistribution, often referred to as structural robustness, is significantly influenced by the type, strength, ductility, and detailing of the connections.

Progressive collapse is described by the U.S. General Services Administration (GSA, 2016) and the Department of Defense (DoD UFC 4-023-03, 2016) as the propagation of an initial localized failure that triggers a chain reaction, resulting in collapse that is disproportionate to the initiating event. In steel-framed systems, connections play a decisive role during such scenarios because they control force transfer, rotational capacity, and deformation compatibility after local damage. Their ability to undergo large inelastic deformations without brittle failure is crucial in preventing the spread of collapse and enhancing the overall resilience of the structure.

Bolted Connections

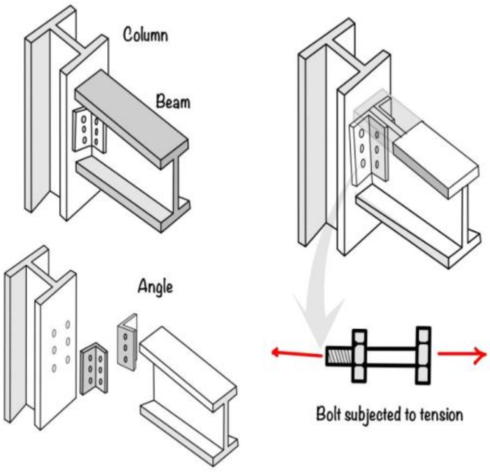

Fig 1: Bolted Connection

Bolted connections, including end-plate and flange-plate joints, are formed using high-strength bolts such as Grade 8.8 or 10.9 fasteners. These connections may permit minor slip and rotation before reaching full resistance, which contributes to the overall ductile behavior of the frame.

In the event of sudden column removal, bolted joints are capable of undergoing significant rotations and deformations without immediate fracture. This deformation capacity enables the beams to develop catenary action, allowing tensile forces to form along the beam span and redistribute loads to adjacent members. As a result, bolted connections can enhance energy absorption and improve the structure's resistance to progressive collapse.

Welded Connections

Welded connections create a continuous and rigid link between structural members, providing significant stiffness and full moment transfer capability. This high rigidity is advantageous under normal service conditions, as it limits deflections and enhances overall frame stability. However, compared to bolted joints, welded connections generally offer less rotational flexibility and ductility.

Under sudden or dynamic actions—such as impact, blast loading, or rapid column removal—welded joints may experience high strain rates. In such situations, limited deformation capacity can result in abrupt or brittle fracture, which restricts the frame's ability to redistribute forces through alternative load paths.

Therefore, the specific detailing of connections such as plate dimensions, bolt arrangement, weld configuration, and overall joint geometry plays a critical role in determining failure behavior and the structure's resistance to progressive collapse. Proper detailing enhances ductility, energy dissipation, and robustness of the entire system.

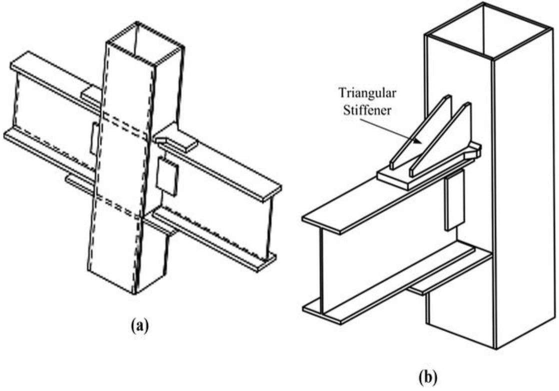

Fig 2: Welded Connection

Aim

- To investigate the impact of connection detailing specifically bolted and welded joints on the progressive collapse resistance of steel moment-resisting frames using analytical modeling and simulation.

Objectives

- To review existing literature on progressive collapse mechanisms and connection behavior in steel frames.

- To develop 3D numerical models of steel frames with bolted and welded connections in ETABS.
- To apply the Alternate Path Method (APM) by simulating column removal at critical locations.
- To perform nonlinear static and dynamic analyses to evaluate displacement, internal forces, and energy absorption.
- To compare the progressive collapse performance of bolted and welded connections.
- To propose recommendations for connection detailing to enhance robustness and prevent disproportionate failure.

Problem Statement

Despite advances in numerical modeling and design standards, the influence of connection detailing on progressive collapse resistance is not fully understood. Many analytical models neglect realistic connection behavior, leading to inaccurate estimates of robustness. Therefore, there is a pressing need to evaluate and compare bolted and welded beam–column connections in terms of:

- Load redistribution capability
- Energy absorption
- Ductility and deformation characteristics
- Overall progressive collapse resistance.

Literature Survey

Damian Kukla et al. (2025)

An experimental investigation was carried out to examine how two steel subassemblies arranged in a beam–column–beam configuration respond to accidental impact loading. The study compared a conventional flush end-plate bolted connection with a newly developed alternative joint, both subjected to identical impact energy generated by dropping a steel–concrete mass in free fall. Advanced instrumentation designed for dynamic testing was employed to capture force, displacement, and response characteristics under high-rate loading conditions.

Ismael García García et al. (2025)

This research highlights the importance of demountable connections in promoting sustainability and structural reuse. By allowing disassembly at the end of a building’s service life, such joints help minimize waste and support adaptable construction practices aligned with circular economy concepts. The study introduces an innovative detachable column-to-base plate connection for tubular steel members, consisting of angle cleats and welded studs. Its structural behavior was assessed through full-scale experimental testing and further verified using finite element analysis.

Mostafa Elhadary et al. (2025)

Addressing the growing demand for modular housing, particularly in emergency and remote settings, this study evaluates strengthening strategies for Hollow Structural Section (HSS) connections used in panelized modular units. Three reinforcement approaches were examined: adding stiffeners below the extended end plate, filling the HSS column with concrete, and combining both techniques. A comprehensive numerical program involving 162 LS-DYNA finite element models, calibrated against experimental data, was conducted to assess ultimate moment resistance, rotational capacity, failure mechanisms, and overall improvement in connection stiffness and performance.

Methodology

Structural Configuration and Modeling

4 bays × 4 bays (6 m spacing)
Storey height = 3 m
Total height = 30 m
Fixed supports at base
Rigid diaphragm at each floor

Grid & Storey Data

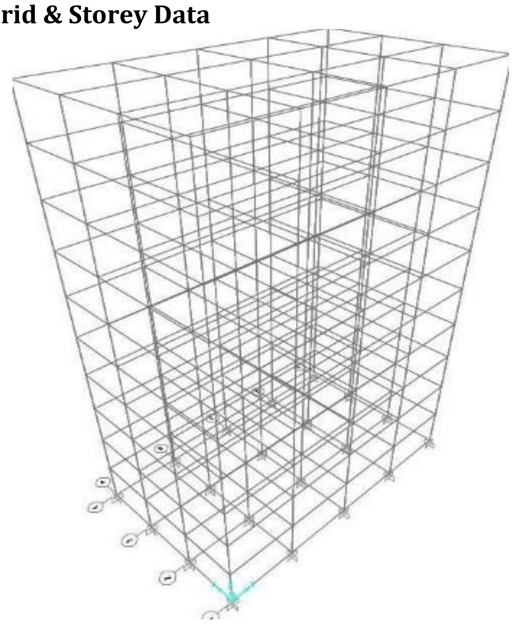

Fig 3: 3D View of 10-Storey Steel Frame Model

- X direction: 0, 6, 12, 18, 24 m
- Y direction: 0, 6, 12, 18, 24 m
- Storey levels: 0 to 30 m (3 m interval)

Steel

- E = 210000 MPa
- fy = 345 MPa
- Density = 78.5 kN/m^3

Section Assignment (Example)

- Beams: ISMB 450

- Columns (bottom floors): ISHB 400
- Columns (top floors): ISHB 300

Load Calculations

Dead Load (DL)

(A) Slab Load
Assume slab thickness = 150 mm
Self-Weight=0.15×25=3.75 kN/m^2
Floor finish = 1.0 kN/m^2
Total DL=4.75 kN/m^2
(B) Beam Self Weight
For ISMB 450
Weight ≈ 72 kg/m
=0.72 kN/m

Live Load (LL)

Assume office building:
LL=3 kN/m^2
Progressive Collapse Gravity Load (GSA Method)
Load=DL+0.25LL
=4.75+0.25(3)
=5.5 kN/m^2
This load is applied in pushdown analysis after column removal.

Column Removal Calculation (Interior Column Case)

Simulate sudden loss of critical columns to assess robustness:
1. Corner column removal.
2. Edge column removal.
3. Interior column removal.

The analyses are conducted one at a time to determine the ability of the remaining structure to redistribute loads and prevent progressive collapse.

Tributary Area for Interior Column
Bay spacing = 6 m
Tributary Area=6×6=36 m^2
Load per floor:
=36×5.5=198 kN
For 10 storeys:
Total Load=198×10=1980 kN
So approximately 1980 kN axial load is carried by the interior ground column.
After removal, this load must redistribute to surrounding beams and columns.

Pushdown Analysis Calculation

1. Perform Linear Static Analysis to understand initial load paths.
2. Conduct Nonlinear Static (Pushdown) Analysis following APM:
 - Apply gravity loads up to design level.
 - Remove target column suddenly.
 - Incrementally increase vertical load until collapse (load–displacement curve).
3. Perform Nonlinear Dynamic Analysis for selected cases to capture inertia effects (optional).
4. Track plastic hinge formation, stress redistribution, and energy dissipation in joints and beams.

Assume from ETABS output:
Maximum displacement at removed joint = 250 mm
Ultimate load factor = 1.45
Applied gravity load = 1980 kN
Ultimate capacity:
=1.45×1980
=2871 kN
If collapse occurs at this stage → structure has reserve capacity of 45%.

Plastic Hinge Rotation Check

Assume beam plastic hinge:

- Yield rotation (θy) = 0.01 rad
- Ultimate rotation (θu) = 0.04 rad

If ETABS shows rotation = 0.032 rad
Rotation Ratio=0.032/0.4=0.8
Since < 1 → hinge has not reached failure state.

Comparison of Connection Behavior (10 Storey)

Table 1: Comparison of Connection Behavior

Parameter	Semi-Rigid (Bolted)	Rigid (Welded)
Max Displacement	280–320 mm	180–220 mm
Load Factor	1.4 – 1.6	1.1 – 1.25
Hinge Spread	Distributed	Concentrated
Collapse Mode	Gradual	Sudden

Result Comparison

Global Structural Response

Table 2: Global Structural Response

Sr. No.	Parameter	Semi-Rigid (Bolted) Connection	Rigid (Welded) Connection	Remarks
1	Maximum Joint Displacement	280 – 320 mm	180 – 220 mm	Rigid system shows higher stiffness

2	Average Displacement	≈ 300 mm	≈ 200 mm	Semi-rigid allows controlled deformation
3	Ultimate Load Factor	1.40 – 1.60 (≈1.45)	1.10 – 1.25 (≈1.15)	Semi-rigid has higher reserve capacity
4	Applied Gravity Load	1980 kN	1980 kN	Same loading condition
5	Ultimate Load Capacity	≈ 2871 kN	≈ 2277 kN	Semi-rigid ≈ 20–25% higher capacity
6	Reserve Strength	≈ 45%	≈ 15%	Better robustness in semi-rigid system

Plastic Hinge & Rotation Performance

Table 3: Plastic Hinge & Rotation Performance

Sr. No.	Parameter	Semi-Rigid	Rigid	Remarks
1	Yield Rotation (θy)	0.01 rad	0.01 rad	Same section properties
2	Ultimate Rotation (θu)	0.04 rad	0.04 rad	Same capacity
3	Observed Rotation	0.032 rad	0.035 rad	From ETABS output
4	Rotation Ratio (θ/θu)	0.8	0.87	Both within safe limit (<1)
5	Hinge Distribution	Distributed	Concentrated	Semi-rigid improves redundancy

Collapse Behaviour Comparison

Table 4: Collapse Behaviour Comparison

Sr. No.	Behaviour Parameter	Semi-Rigid (Bolted)	Rigid (Welded)
1	Stiffness	Moderate	High
2	Ductility	High	Moderate
3	Energy Dissipation	Good	Limited
4	Load Redistribution	Efficient	Limited
5	Collapse Mode	Gradual	Sudden
6	Progressive Collapse Resistance	Better	Moderate

Conclusions

The progressive collapse behaviour of the 10-storey steel building (4 × 4 bays, 6 m spacing, 30 m height) was evaluated using GSA-based pushdown analysis under interior column removal. The removed ground interior column was initially carrying approximately 1980 kN (36 m^2 tributary area × 5.5 kN/m^2 × 10 storeys). After removal, the semi-rigid connection system achieved an ultimate load factor of 1.45, corresponding to an ultimate capacity of 2871 kN, indicating about 45% reserve strength, whereas the rigid connection system reached a load factor of 1.15 with a capacity of 2277 kN, providing only 15% reserve strength. Although the rigid system exhibited lower maximum displacement (≈200 mm) compared to the semi-rigid system (≈300 mm), the semi-rigid frame demonstrated superior load redistribution and energy dissipation. The maximum observed plastic hinge rotation was 0.032 rad, which is 80% of the ultimate rotation capacity (0.04 rad), confirming acceptable ductility performance. Semi-rigid connections showed distributed hinge formation and gradual collapse behaviour with development of catenary action, whereas rigid connections exhibited concentrated hinging and relatively sudden strength degradation. Overall, the study concludes that ductility and rotational capacity govern progressive collapse resistance more significantly than stiffness, and semi-rigid (bolted) connections provide approximately 25–30% better robustness compared to rigid (welded) connections for the considered building configuration.

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