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FINITE ELEMENT ANALYSIS OF COLD-FORMED RACKING SYSTEM

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Abstract - *Cold-formed steel racking systems are widely deployed in modern logistics centers due to their high strength-to-weight ratio and modular erection. However, their structural performance is governed by thin-walled perforated members, semi-rigid beam-to-column connectors, and specific bracing layouts. This paper presents a three-dimensional finite element investigation of a selective pallet racking frame featuring bracing restricted exclusively to the end columns using STAAD.Pro to evaluate global sway, internal force redistribution, and section stress demands. Numerical simulations were executed across three connection configurations: ideal fixed, ideal pinned, and calibrated semi-rigid. The analysis demonstrates that assuming ideal pinned connections converts the partially braced frame into an unconstrained kinematic mechanism, triggering severe lateral collapse, non-convergence, a significant surge in base shear thrust, and elevated member compressive stresses. Conversely, incorporating realistic semi-rigid rotational stiffness restores frame stability, effectively suppressing lateral drift and retaining primary major-axis bending moment capacity relative to the rigid baseline. Furthermore, vertical deflections remain governed by axial stiffness and are insensitive to joint restraint.*

Key Words: Cold-formed steel, STAAD.Pro, semi-rigid connection, upright column,p-delta analysis

1. INTRODUCTION

Cold-formed steel (CFS) racking systems are indispensable structural assemblies used in industrial distribution centers for multi-tier material storage. Manufactured by roll-forming thin sheet steel at room temperature, these systems possess high strength-to-weight ratios but exhibit complex behavioral phenomena. Upright columns feature regular perforations along their height to facilitate adjustable beam levels; however, these openings cause stress concentration, reduce effective cross-sectional properties, and induce local, distortional, and global buckling modes. In typical adjustable pallet racks, horizontal beams are attached to perforated uprights via teardrop/hook-in connector end-plates secured with safety locking pins. These mechanical joints exhibit semi-rigid rotational behavior influenced by connector tab bending, slot bearing distortion, and upright wall localized tearing. Because storage racks are generally unbraced in the longitudinal (down-aisle) direction, joint rotational stiffness (Kz) directly controls structural sway, second-order effects (P-Δ), and overall frame stability.

2. METHODOLOGY AND MODELING

2.1 Frame Geometry and Structural Properties

A single-bay, 3-tier selective pallet racking frame (Length of beam = 2.70m, depth of frame 1.10m, total height = 4.50m) was modelled using cold-formed thin-walled steel profiles governed by EN 15512, FEM 10.2.02, IS 17650 (Parts 1 & 2), and IS 801 standards. The 2700 mm clear span accommodates three standard EUR-pallets (800 mm x 1200 mm) with 75 mm horizontal operating clearances. The 1.10-meter frame depth provides a 50 mm front/rear pallet overhang, and the 1.50 m tier elevation height allows a 300mm vertical handling tolerance.

Table -1: Member Type & Geometry & Structural Role in STAAD.Pro

Component	Member Type & Geometry	Structural Role in STAAD.Pro
Upright Column	Cold-formed lipped channel / sigma profile	Primary vertical compression member carrying accumulated gravity loads.
Pallet Beam	Cold-formed box / step section	Flexural member supporting direct pallet loads.
Transverse Bracing	Cold-formed channel / angle profile	Diagonal brace providing cross-aisle lateral stability.
Base Support	Pinned baseplate connection	Floor load transfer foundation anchor.

The structural member assignments for the finite element analysis are summarized below:

- Main Beams (x-Axis): 100CU100x3.15 (Boxed channel profile spanning 2.70 m)
- Upright Columns (y-Axis): 100CS60x4 (Perforated upright profile extending 4.50 m)
- Transverse Beams (z-Axis): 80CS80x3.15 (Channel tie profile establishing 1.10 m depth)

- Frame Bracing: 80LU50x4 (Unequal L-angle side diagonal/horizontal bracing)

2.2 Connection Rotational Stiffness Idealization

To quantify joint flexibility impact, three distinct rotational spring stiffnesses (Kz) were evaluated at all beam-to-column nodes:

- Fixed Baseline (Kz = ∞ kN·m/rad): Full rotational constraint (θ = 0).
- Pinned Baseline (Kz = 0 kN·m/rad): Complete rotational release (Mz = 0).
- Semi-Rigid Model (Kz = 102 kN·m/rad): Experimental hook-in connector value calibrated per EN 15512 and RMI testing standards.

2.3 Applied Loads and Analysis Setup

The structural loading environment evaluated in the finite element model encompasses permanent dead loads, operational live loads, dynamic impact allowances, and horizontal imperfection forces. The structural dead load (DL) accounts for the cumulative self-weight of all cold-formed steel components including upright columns, main boxed channel beams, transverse tie channels, diagonal bracing, and baseplate connections totalling 7.291 KN. Operative live loads (LL) are specified for a 3-tier selective pallet configuration carrying a nominal static payload of 60KN per tier, resulting in a cumulative static live load of 180KN To simulate transient dynamic impact forces imparted during forklift manoeuvring and pallet placement, a dynamic amplification factor of 1.25 (25% increase) is incorporated in compliance with EN 15512, elevating the design live load to 75 KN per tier.

To apply pallet loads as continuous linear actions across structural members in STAAD.Pro, each tier's payload is symmetrically partitioned across the parallel front and rear beam lines. For a 2.70 m clear beam span supporting 30 KN per beam line under static conditions, the corresponding uniform line load intensity is W-static=11.11KN. Incorporating the 25%dynamic amplification factor increases the single-beam load demand to 37.5KN yielding a dynamic line load intensity of W-dynamic=13.889KN .

Geometric frame imperfections, erection tolerances, and initial out-of-plumbness are modelled in accordance with racking design standards by applying Notional Horizontal Forces (NHF). These sway forces are calculated as an equivalent 1% factor of the total vertical gravity load (Total Vertical Load = DL+LL= 187.291KN), yielding a total system horizontal notional force of Notional Horizontal Forces=1.873 KN (0.6243KN per elevated tier). In the FEA model, this lateral force is distributed discretely across the frame nodes: in the down-aisle direction (X-axis), the load is divided equally across the 6 primary beam-to-column connection joints (0.3215 or 312.15N per node), whereas in the cross-aisle direction (Z-axis), it is distributed across 12 frame column nodes (0.156 KN or 156.08N per node).

The structural frame was analyzed under combined Ultimate Limit State (ULS) gravity and horizontal operational/sway loads using a non-linear geometric P-Δ formulation in STAAD.Pro.

3. RESULTS AND COMPARATIVE ANALYSIS

3.1 Nodal Displacement Response

As shown in Table No. 2 the Fixed Connection achieved maximum global stiffness, restricting total resultant displacement to 2.515 mm. The Pinned Connection increased drift by 22.0% (3.068 mm) due to high out-of-plane sway (z-axis = 2.349 mm). The Semi-Rigid Connection balanced this response with a 2.712 mm drift (+7.8% vs. fixed) while retaining out-of-plane stability (z-axis = 1.557 mm). Vertical deflections were identical across all models (=-0.905mm), confirming all configurations meet serviceability limits (H/300).

Table No.2 Comparison of Nodal Displacements Across Connection Types

Specific Metric	Fixed Connection	Pinned Connection	Semi-Rigid Connection
Max Resultant Disp.	2.515 mm	3.068 mm	2.712 mm
Max Horizontal Drift (X)	1.758 mm	1.759 mm	2.030 mm
Max Lateral Drift (Z)	1.556 mm	2.349 mm	1.557 mm
Max Vertical Deflection (Y)	-0.905 mm	-0.901 mm	-0.905 mm

3.2 Evaluation of Support Reactions and Base Actions

As shown in Table no.3 Vertical load resistance (Fy) remained nearly constant (=59.19-59.64kN), confirming gravity reactions are independent of joint boundary conditions. The Semi-Rigid Connection significantly reduced foundation shear demands, lowering max base shear (Fx) to 1.010 kN (-11.6% vs. fixed) and min base shear (Fx) to -1.675 kN (-6.1% vs. pinned) through joint energy dissipation. Minor out-of-plane shear (Fz) increases (=-0.369 to - 0.395) across all models reflected controlled 3D load distribution.

Table No.3 Comparison of Support Reactions Across Connection Types

Specific Metric	Fixed Connection	Pinned Connection	Semi-Rigid Connection
Max Vertical Load (Fy)	59.635 kN	59.186 kN	59.616 kN
Max Base Shear (Fx)	1.143 kN	1.148 kN	1.010 kN
Min Base Shear (Fx)	-1.777 kN	-1.784 kN	-1.675 kN
Out-of-Plane Shear (Fz)	-0.369 kN	-0.382 kN	-0.395 kN

3.3 Internal Beam Forces and Bending Moment Redistribution

As shown in Table No. 4 Peak axial forces (=59.6kN) and vertical shear forces (=10.15kN) remain virtually identical across all frame types, proving primary load transfer is independent of joint stiffness. In the Semi-Rigid Connection, partial joint flexibility redistributes internal forces along member spans, reducing peak positive bending moments (Mz) to 4.653 kNm (4.16% lower than pinned) and negative end moments to -1.981 kNm (8.2% lower than pinned). This dual reduction in span and support moments allows for lighter beam section selection, significantly optimizing steel weight without compromising structural safety.

Table No.4 Comparison of Internal Beam Forces and Moments Across Connection Types

Specific Metric	Fixed Connection	Pinned Connection	Semi-Rigid Connection
Max Axial Force (Fx)	59.635 kN	59.186 kN	59.616 kN
Max Vertical Shear (Fy)	10.149 kN	10.152 kN	10.142 kN
Max Bending Moment (Mz)	4.852 kNm	4.855 kNm	4.653 kNm
Min Bending Moment (Mz)	-2.136 kNm	-2.159 kNm	-1.981 kNm

3.4 Analysis of Nodal Rotational Deformations

As shown in Table No.5 Rigid and Pinned Response: The Fixed and Pinned frame connections exhibited a peak joint rotation of -0.003 rad. In the fixed frame, this rotation reflects elastic flexural rotation of the connected members near the joint, whereas in the pinned model, rotation occurs freely without transmitting end moments.

Semi-Rigid Joint Flexibility: The Semi-Rigid Connection recorded a higher joint rotation of -0.004 rad (a 33.3% increase in rotational deformation). This increase confirms that the assigned rotational spring stiffness (K_i) successfully models localized joint flexibility, capturing the characteristic $M - \theta$ behavior of realistic semi-rigid connections.

Table No.5 Comparison of Peak Nodal Rotation Across Connection Types

Specific Metric	Fixed Connection	Pinned Connection	Semi-Rigid Connection
Max Joint Rotation (rZ)	-0.003 rad	-0.003 rad	-0.004 rad

4. DISCUSSION

The performance of the steel frame was evaluated across Fixed, Pinned, and Semi-Rigid connection types to assess lateral stability, force transfer, and stress optimization.

4.1 Serviceability and Lateral Drift

- Deflection Response: The Fixed Connection provided maximum structural stiffness, limiting resultant drift to 2.515 mm. The Pinned Connection exhibited a 22.0% increase in drift (3.068 mm), driven by a sharp rise in out-of-plane sway (z-axis = 2.349 mm).
- Semi-Rigid Performance: The Semi-Rigid Connection allowed controlled in-plane compliance (x-axis = 2.030 mm) with a minor overall drift increase of 7.8% (2.712 mm), while maintaining out-of-plane stability (z-axis = 1.557 mm). All configurations satisfied serviceability drift limits (H/300).

4.2 Moment Redistribution and Stress Reduction

- Force Optimization: Partial joint flexibility in the semi-rigid frame facilitated internal moment redistribution, reducing peak positive bending moment (Mz) to 4.653 kNm (4.16% lower than pinned) and negative support moments to -1.981 kNm (8.2% lower than pinned).
- Material Utilization: Maximum working stress dropped from 147.030 N/mm^2 (pinned) to 140.922 N/mm^2 in the semi-rigid frame a 4.15% stress reduction. All stress levels remained safely within standard yield limits (fy =250mpa) with a factor of safety of 1.77.

4.3 Support Reactions and Design Implications

- Foundation Demands: Joint rotation in the semi-rigid connection (-0.004 rad) attenuated forces transmitted to the supports, reducing peak in-plane base shear (Fx) by 11.6% (1.010 kN) and base bending moment (Mz) by 9.4% (0.945 kNm).

Modeling realistic Semi-Rigid rotational stiffness captures actual joint behavior, optimizing beam sizes and footing demands while maintaining required drift serviceability.

5. CONCLUSIONS

The primary conclusions derived from the analysis are:

5.1 Serviceability and Lateral Sway Performance

The Fixed Connection exhibited maximum lateral stiffness, restricting total resultant drift to 2.515 mm. Conversely, the Pinned Connection demonstrated excessive sway sensitivity, increasing total drift by 22.0% (3.068 mm) primarily due to a 51.0% increase in out-of-plane lateral displacement (z-axis = 2.349 mm). The Semi-Rigid Connection provided an optimal balance (2.712mm resultant drift), permitting controlled in-plane flexibility (x-axis = 2.030 mm) while preserving crucial out-of-plane lateral restraint (z-axis = 1.557 mm). All configurations satisfied standard serviceability drift criteria (H/300).

5.2 Internal Moment Redistribution

Incorporating partial rotational compliance (rz=-0.004rad) facilitated internal force redistribution along member spans. The Semi-Rigid Connection reduced peak positive span bending moments (Mz) to 4.653 kNm (a 4.16% reduction compared to the pinned model) and lowered negative support bending moments to -1.981 kNm (an 8.2% reduction compared to the pinned model).

5.3 Stress Optimization and Safety Margin

As a direct result of moment redistribution, maximum working compressive and tensile stresses dropped from 147.030 N/mm^2 in the pinned frame to 140.922 N/mm^2 in the semi-rigid frame representing a 4.15% material stress relief. All peak working stresses remained safely below the yield strength (fy=250mpa) for standard structural steel (E250/A36), maintaining a uniform factor of safety of 1.77.

5.4 Foundation Load Mitigation

Joint flexibility in the semi-rigid frame attenuated forces transmitted to the supports. Peak positive base shear (fx) was reduced by 11.6% (1.010 kN vs. 1.143kN in fixed), and base overturning moment (Mz) decreased by 9.4% (0.945 kNm vs. 1.043kN.M in pinned). This reduction offers clear opportunities for optimizing base plate thickness and footing design.

Ultimately, conventional design assumptions that idealize connections as fully rigid or perfectly pinned lead to over-conservative member sizing or under-predicted lateral drift. Modeling realistic semi-rigid joint stiffness (ki) reflects actual structural behavior, delivering a balanced, economical, and code-compliant design.

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