NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

Numerical & Experimental Seismic Analysis of Cold-Formed Steel Pallet Rack Connections in The Down-Aisle Direction

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ABSTRACT

The increasing use of decentralized manufacturing and on-demand delivery systems has led to a greater need for effective large-scale storage solutions. Consequently, pallet racking systems made from cold-formed steel have been widely adopted because of their light weight and effectiveness for large scale storage. However, these structures, characterized by their slender, intricate cross-sections and semi-rigid connections with complex load distributions, have shown unpredictable and sometimes unsatisfactory performance during major seismic events. Substantial financial losses have been documented in recent severe earthquakes, such as those in Canterbury (2010/2011) and Kaikoura (2016) in New Zealand. This study aims to determine the rotational capacity of beam-end connections in selective pallet racking systems using an improved cantilever-testing method. In addition, a validated numerical model was utilized to accurately predict the moment capacity of the beam-to-upright connection. By investigating the seismic performance of beam end connectors, this study seeks to enhance the understanding of the weaknesses of these systems, facilitating the development of more durable and earthquake-resistant designs.

1 INTRODUCTION

Pallet racking systems have become integral to global supply chains in warehouses, storing and organizing palletized goods efficiently. Built from lightweight cold-formed steel, they are designed for the swift placement and retrieval of diverse products. Their lightweight nature and high imposed loads distinguish them from the conventional structures (Freitas et al. 2005; Shah et al. 2016; Castiglioni 2016). As shown in Figure 1, selective pallet racking is common in warehouses. It comprises upright columns supporting the roof and pallet beams, constructed from prefabricated thin-walled components and horizontal built-up closed sections (Castiglioni 2016; Dai 2018). The main challenges in determining the structural behavior of pallet racks are their complex buckling modes, semi-rigid beam-upright connections and base plate joints. The seismic behavior of selective steel pallet storage racks is less predictable and resilient than heavy steel framed construction because of these challenges (Kanyilmaz et al. 2016). This vulnerability has caused significant economic losses during severe earthquakes and has disrupted product supply chains. For example, damage to a cheese factory after the 2012 Emilia Romagna Earthquake was estimated at €150 million (Kanyilmaz et al. 2016). Losses of up to NZ$ 50 million from pallet racking collapses during the 2010 and 2011 Canterbury earthquakes were reported by Crosier et al. (2010) and Uma and Beattie (2011).

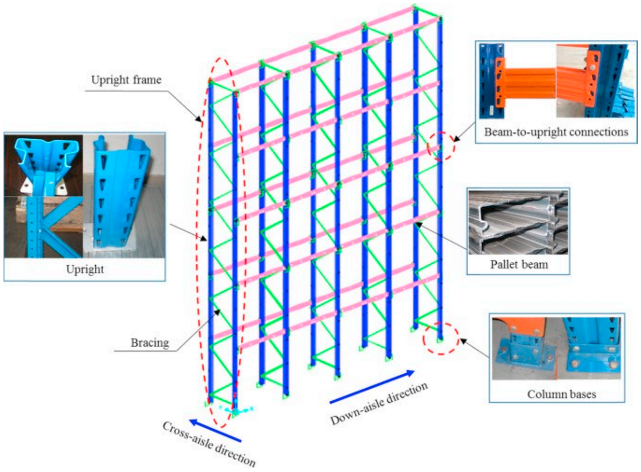


Figure 1: Configuration of the steel storage-selective pallet racks (Dai et al. 2018)

In the down-aisle direction of the moment frame, attention has been given to the beam-upright connections due to their significant impact on the seismic performance of the rack system. Currently, two conventional connections (specifically, boltless and bolted connections) with varying performance have been employed in selective pallet racking systems. In the case of boltless connections, pallet beams are connected to uprights using tabs or hooks from the end connector, without the use of welds or bolts. Compared with bolted connections, these connections were found to be more ductile and flexible. Dissipation of the seismic force in these connections was achieved through steel yielding and fracturing in the endplate.

Meanwhile, bolted connections, which are semi-rigid and expensive, have been used to fix the beam to the upright position to store heavier objects. (Bernuzzi and Castiglioni 2001, Zhao et al. 2018, and Gusella et al. 2018).

This research has focused on simulating the seismic performance of pallet racking systems in the down-aisle direction using the numerical analysis software ABAQUS and OpenSees. The simulation results have been validated through experimental data obtained from modified cantilever tests that examined the moment-rotation characteristics of beam-to-column connections under simulated seismic forces. The numerical models have been further enhanced by incorporating material properties derived from tensile coupon tests of Cold-Formed Steel (CFS), which provided data on the yield strength, ultimate tensile strength, and elongation at failure under various strain rates. This combined numerical and experimental approach has enabled accurate prediction of the structural behavior and moment capacity of beam-to-upright connections during seismic events.

The integration of known mechanical properties of the components, moment-rotation capacity assessment, and numerical analyses has enhanced the understanding of the seismic behavior of pallet racking systems and the applicability of CFS for such applications. Numerical modelling and evaluation can significantly augment our experimentally based understanding of pallet rack connection behaviour. These insights will be instrumental in developing more resilient pallet storage rack systems capable of effectively resisting seismic forces, reducing the need for expensive component and system experimental testing.

2 EXPERIMENTAL TESTS UNDERTAKEN

The study employed two principal types of experimental test: a tensile coupon test and a modified cantilever test to assess seismic performance and determine material properties.

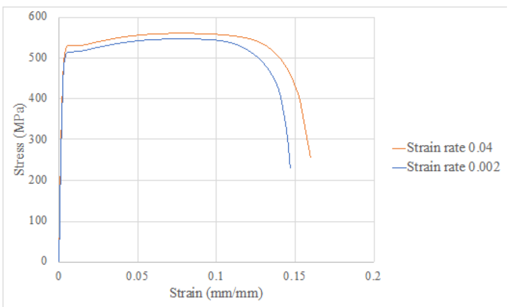
2.1 Tensile coupon test

Three types of cold-formed steel were tested: 2 mm thick material for uprights, 4 mm thick material for beam-end-connectors and 1.5 mm thick material for beams.

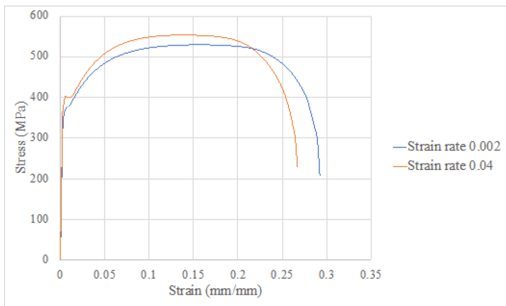
Tension coupon tests were conducted according to ASTM E8/E8M-21 standards using a 50 kN MTS machine. The tests were performed at strain rates of 0.002 mm/sec and 0.04 mm/sec, with three samples per configuration. The stress-strain relationships and material properties were determined from the test data and are presented in Figure 2 and Table 1.

Table 1: Engineering and plasticity parameters

	Strain rate: 0.002 (s^{-1})			**Strain rate: 0.04 (s^{-1})**		
	E (Mpa)	0.2% offset F_y (Mpa)	F_{max} (Mpa)	E (Mpa)	0.2% offset F_y (Mpa)	F_{max} (Mpa)
1.5 mm beam material	222000	332.00	429.08	217000	370.00	447.08
2 mm upright material	220000	514.00	547.05	224000	528.00	560.88
4 mm BEC material	211000	371.00	529.40	211000	384.00	554.02



(a)



(b)

(c)

Figure 2: The average stress-strain curves with strain rates 0.002 and 0.04 of a) 2 mm material, b) 4 mm material and c) 1.5 mm material

2.2 Cantilever test procedure

A total of 10 tests on left-handed beam end connectors were conducted on Boxed Beam 100x40 and Upright 90M. The testing rig modified the setup in the AS 4084 (2023) standard, in which a load F amounting to 10% of the anticipated failure load is initially applied and then withdrawn as a preload. Instead, the tests began with a 128 kg weight placed 100 mm from the Beam End Connector which remained throughout the experiments. This setup represents the pallet vertical load, improves moment rotation capacity estimation, reduces gap impacts, and minimizes hook slippage (Bové et al., 2022).

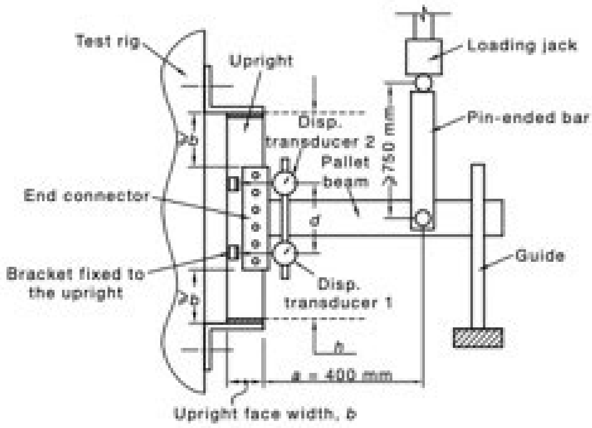


Figure 3: Test rig of beam end connector bending test with a specimen during testing

The rotation between the beam and column was produced by loading the cantilever beam end with a hydraulic jack 400 mm from the upright face, allowing free in-plane rotation per AS 4084 with a pin length of over 750 mm. The load was incrementally increased until a further increase was unfeasible, monitored by a load cell, with rotations measured by two LVDTs to ascertain relative rotation. Three samples of each beam-upright combination were tested under monotonic and cyclic loadings. The cantilever moments and moment versus rotation data are shown in Figure 4, and the moment capacity and failure modes are listed in Table 2.

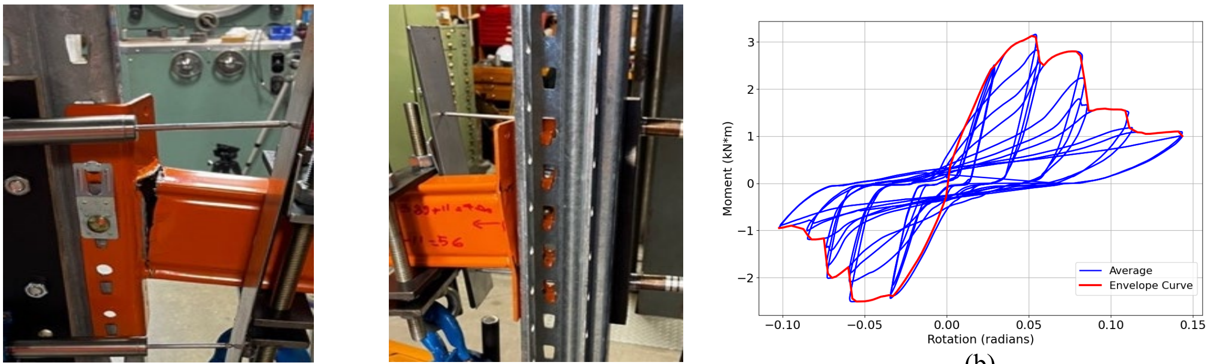
Damage Assessment: Two main failure modes were identified: (i) damage occurring at the BEC-beam junction (Fig. 4.a), which initiated from the top right corner of the boxed beam and extended to the left middle side, serving as the dominant failure mode for the Beam 100x40-90M sample; (ii) tabs cutting into the upright (Fig. 4.b), where the top tab deformed and cut 1-2 mm into the upright.

2.3 Discussion on the experimental results

Comprehensive insights into the moment rotation behavior of semi-rigid beam-to-column connections in selective pallet racking systems were obtained experimentally. Tensile coupon tests on the two cold-formed materials showed compatibility with predefined properties and minimal strain rate influence. The stress–strain curves provided the essential mechanical properties for numerical modelling. Damage assessments revealed vulnerabilities, particularly at Beam End Connector (BEC) connections, with cracks appearing at high rotations. The combinations with the highest peak moment capacity exhibited the lowest rotational capacity.

Table 2 - Beam End Connector Test Results

BEC Type	Beam Type	Upright Type	Upright Thickness (mm)	Moment Capacity (kNm)	Failure Modes
B100x40-90M	100x40	90M	2.00	3.08	i and ii



(a) (a) (b)

Figure 4: failure modes of a) failure modes, b) Moment-rotation curve of 100x40-90M Sample

3 NUMERICAL ANALYSES

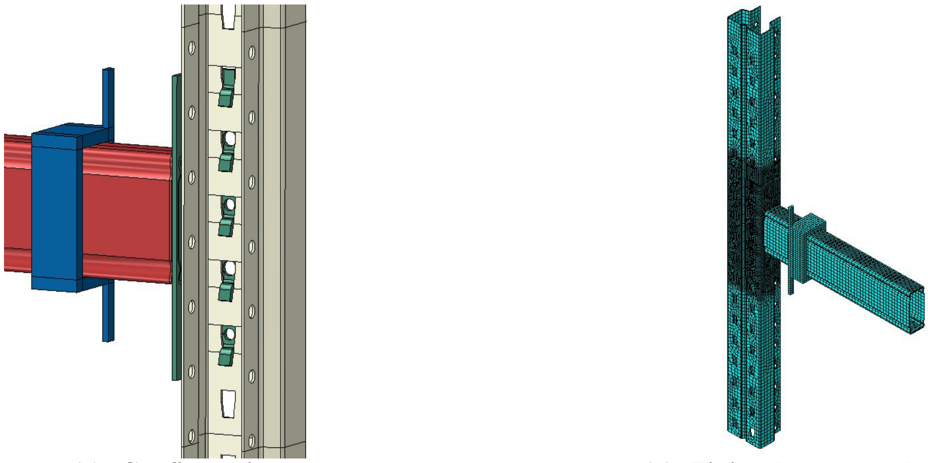
3.1 ABAQUS modeling

Analytical models in ABAQUS were developed to determine the ductile damage parameters by simulating the monotonic cantilever tests, using the mechanical properties from the coupon tests. C3D8R elements were used for all the parts. The elastic and plastic parameters were sourced from Table 1 and Figure 2, respectively. Ductile damage analysis, based on a 1.5 mm steel tension test, identified damage initiation using a yield stress criterion and damage evolution with a fracture strain criterion. As the damage progressed, the stress-bearing capacity diminished, leading to failure. The detailed parameters and outcomes are presented in Table 3, and these are included in the cantilever test simulation.

Table 3- Ductile damage parameters

Fracture Strain	Stress Triaxiality	Strain Rate	Energy Fracture (N/mm)
0.128	0.33	0.04	3000

In the cantilever test simulation, surface-to-surface interactions were used for tabs and connections, whereas node-to-surface interactions with normal hard and 0.3 friction tangential behavior were used for the others. A tie constraint was used to simulate the weld between the beam and the endplate. The column had fixed base boundary conditions, allowing vertical displacement of the beam. Self-weight and lateral steel plate weights were included for accuracy. The ABAQUS model configuration is shown in Figure 5, and the results for the common Beam 100x40-90M in NZ steel pallet racking are shown in Figure 6.



(a) Configuration **(b) Finite element mesh**

Figure 5: ABAQUS modelling of cold-formed steel pallet racking system beam-end connection.

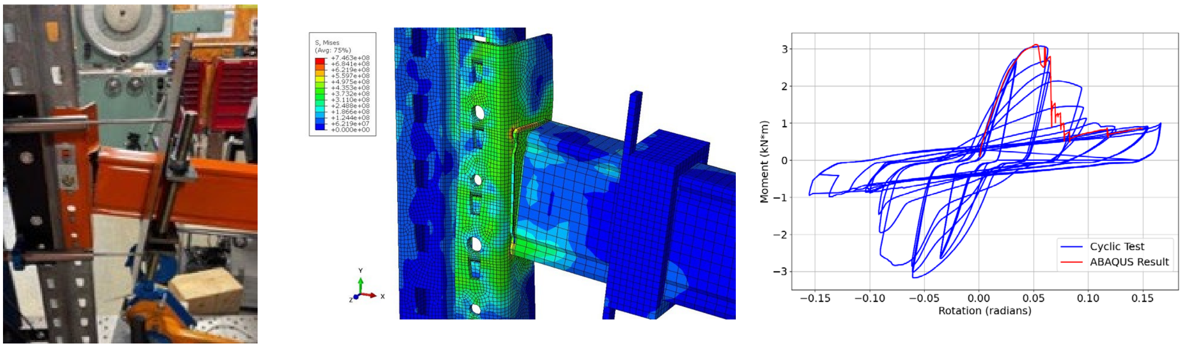


Figure 6: Comparison of ABAQUS simulation and experimental test

3.2 OpenSees modeling

In OpenSeespy (Zhu et al. 2018), the BEC was modelled using the 'Pinching4' material and a zero-length element. The 'elasticBeamColumn' element was utilized for both beams and uprights, with elastic parameters detailed in Table 1 and Figure 2. Table 4 presents the 'Pinching4' material parameters for the BEC in Beam 100 × 40 and upright 90M. The definition of 'Pinching4' material can be found in (Zhu et al. 2018). The verification of the pinching material in comparison to the experimental results is shown in Figure 7.

3.3 Numerical results

The simulations of both the tension coupon test and monotonic cantilever test executed in ABAQUS showed reasonable alignment with the experimental outcomes based on the derived elastic and plastic parameters. The defined ductile damage parameters were reflected with sufficient accuracy in the simulated failure modes, thereby demonstrating the effectiveness of this approach. This alignment was further corroborated when similar analyses were performed using OpenSees. This platform used the findings from the experimental test results to evaluate the nonlinear behavior of steel pallet racks.

The results offer crucial insights into the moment capacity of BECs, which can guide the direction of ongoing research in this area. Moreover, the successful implementation of these analytical models can help minimize the cost of experimental tests and streamline the process of investigating the BEC moment capacity.

Table 4: Pinching4 material for BEC in 100x40-90M

Positive backbone		**Negative backbone**		**Pinching**		**Unloading stiffness degradation**		**Reloading stiffness degradation**		**Strength degradation**	
ePf_1 (kN.m)	1.0	eNf_1 (kN.m)	1.0	rDispP	0.5	gK_1	0.1	gD_1	0.2	gF_1	0.01
ePf_2 (kN.m)	2.75	eNf_2 (kN.m)	2.75	fForceP	0.4	gK_2	0.1	gD_2	0.2	gF_2	0.01
ePf_3 (kN.m)	3.25	eNf_3 (kN.m)	3.25	uForceP	0.01	gK_3	0.1	gD_3	0.2	gF_3	0.01
ePf_4 (kN.m)	1.0	eNf_4 (kN.m)	1.0	rDispN	0.5	gK_4	0.1	gD_4	0.2	gF_4	0.01
ePd_1	0.005	eNd_1	0.005	fForceN	0.4	gKLim	0.4	gDLim	0.3	gFLim	0.01
ePd_2	0.025	eNd_2	0.025	uForceN	0.01					Energy degradation (gE)	10
ePd_3	0.05	eNd_3	0.05							Damage type	cycle
ePd_4	0.15	eNd_4	0.15								

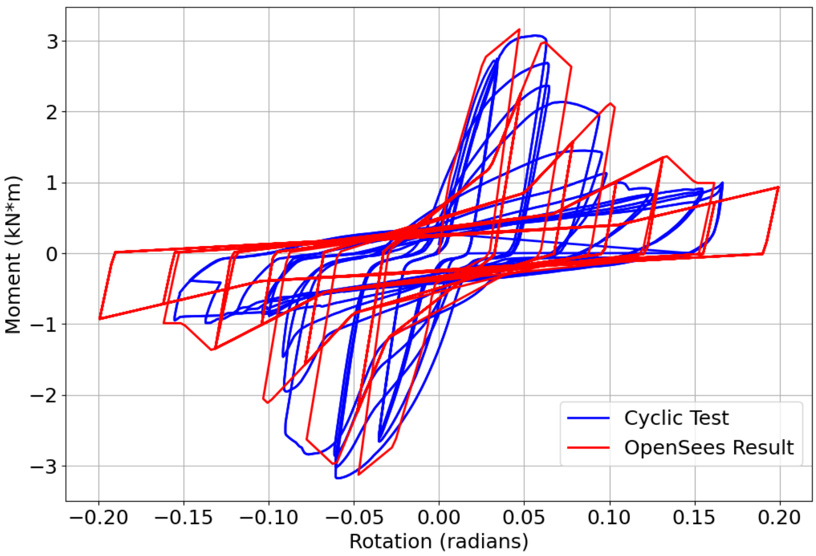


Figure 7: Verification of moment-rotation with cyclic experimental test for 100x40-M90 sample

4 CONCLUSIONS

This study has provided valuable insights into the seismic performance of boltless beam-to-upright connections in pallet racking systems, emphasizing the moment-rotation behavior. Through tensile coupon tests, the distinct properties of 1.5-, 2-, and 4 mm cold-formed materials used for uprights and beam-end connectors were identified. Cantilever tests with various beam and upright configurations highlighted differences in the moment capacity and revealed weaknesses, particularly at the BEC and Beam junctions. The analytical models created in ABAQUS played a crucial role in defining the ductile damage parameters, with results reflecting the performance and potential failure modes of the beam-to-upright connection. The use of OpenSees numerical modeling, ABAQUS, and experimental test results validated the numerical analyses and provided a thorough understanding of the nonlinear behavior of steel pallet racks. This approach also demonstrated the potential to reduce the experimental costs. This research underscores the importance of addressing system vulnerabilities in improving the resilience of pallet racking systems. While the focus was primarily on moment-rotation characteristics through cantilever tests, future studies could expand into other testing methodologies and conduct more detailed numerical analyses for a comprehensive understanding.

ACKNOWLEDGEMENTS

Materials, including beams, uprights, and Beam End Connectors (BEC), used for the experimental study were kindly provided by Dexion NZ. The authors would also like to express their gratitude for the scholarship offered by Callaghan Innovation.

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