
Shake Table Testing of Full-Scale Cold-Formed Steel Pallet Rack in The Down-Aisle Direction

N. Shokrollahi, & G.C. Clifton

University of Auckland, Auckland, New Zealand.

Z. Tang

Dexion, Auckland, New Zealand.

S. Ramhormozian

Auckland University of Technology

ABSTRACT

The seismic resilience of industrial cold-formed steel pallet racking systems is critically important given their complex structural behaviour and the significant economic consequences of failure. This study experimentally investigates the seismic response of two full-scale, two-bay, two-story pallet rack systems with 90 mm deep uprights of different thicknesses subjected to down-aisle shaking table tests. A sequence of scaled historical ground motions was applied, increasing from 25% to nearly 200% of design level intensity demand. The results show that beam-to-upright connections exhibited stable rotational behaviour, with peak rotations of 0.05 radians, indicating the transition from linear to nonlinear response. Systems with thicker uprights demonstrated superior seismic performance, sustaining peak drift ratios up to 7.5% without collapse and showing substantial system-level ductility. The pallet load configuration significantly influenced seismic response, with constrained loads increasing displacement, drift, and rotational demands. The findings provide valuable insight into nonlinear behaviour, support the friction-based isolation concepts in EN 16681 E_{DI} , and quantify dynamic amplification effects to improve seismic resilience.

1 INTRODUCTION

The widespread collapse of industrial pallet racking systems during the 2010/2011 Canterbury and 2016 Kaikoura earthquakes in New Zealand resulted in significant economic losses, primarily due to damage to stored goods and business interruption. Post-earthquake reconnaissance and subsequent research identified the down-aisle direction of these structures as a key area of vulnerability, which underscores the strategic imperative to understand and improve their seismic performance (Kanyilmaz and Castiglioni 2017).

In the down-aisle orientation, the system behaves as a semi-rigid, moment-resisting frame, where the performance of the beam-upright connections is critical to overall stability (Bové et al. 2022). The rotational stiffness and capacity of these connections dictate the frame’s ability to resist lateral loads. Partial failure, leading to a loss of flexural strength, especially at the lowest beam level, can initiate a progressive sway-collapse mechanism, making these connections a primary focus for seismic performance assessment (Kanyilmaz and Castiglioni 2017).

This experimental investigation has been designed to provide a comprehensive evaluation of the seismic behaviour of full-scale pallet racking systems under realistic dynamic loading, with a specific focus on evaluating performance beyond design-level intensities. The primary objectives of this study have been to:

- Determine the rotational capacity and flexibility of beam-upright connections under simulated seismic loading and assess their contribution to global stability at high drift levels.
- Measure the lateral displacements, inter-story drifts, and accelerations to characterise the system’s deformation capacity, ductility reserve, potential failure mechanisms, and dynamic amplification effects, particularly concerning the potential for goods shedding.
- Assess the impact of unit load configuration ("Constrained" vs. "Unconstrained") on the dynamic response and validate the friction-based isolation effects codified in modern standards (e.g., EN 16681).

This paper presents the detailed methodology and principal findings from a series of shaking-table tests conducted on two distinct full-scale pallet rack configurations.

2 EXPERIMENTAL PROGRAM

To achieve the research objectives, a comprehensive experimental program has been designed, involving the construction of a full-scale physical model subjected to simulated earthquake motions on a uniaxial shaking table. This section details the test specimen specifications, the experimental apparatus, the instrumentation plan, and the loading protocol.

2.1 Test Specimen Configuration

The test specimen was configured as a two-bay, two-story selective pallet rack. Each story had a clear height of 1.9 m. To accommodate the physical constraints of the shaking table, shortened 1.35 m beams were used. Two distinct system configurations were tested, differing only in the upright section, as detailed in Table 1.

Table 1: Key Structural Components of the Tested Pallet Rack Systems

Specimen	Upright Section	Beam Section
System 1 – 90M	90M: 90 mm wide x2mm thick	100x40 box
System 2 – 90H	90H: 90mm wide x 2.5mm thick	100x40 box



Simulated unit loads were applied to the rack to represent in-service conditions. Four unit loads were used in total, each weighing 1200 kg. These loads consisted of steel pallets loaded with heavy metal billets, which are shown in Figure 1.

Crucially, two distinct load configurations were investigated to assess the influence of boundary conditions:

1. **Constrained Configuration:** To prevent pallet movement and dislodgement, mechanical restraints were applied. A bolt was fastened beside the pallets on the supporting beam, and the loads were further secured using polyester strops (Figure 2), effectively coupling the unit load mass to the structure (simulating a "Rigid Mass" condition $E_{D2} = 1.0$).
2. **Unconstrained Configuration:** The restraints were removed, allowing the pallets to slide freely on the beams, relying solely on friction for retention (simulating a "Friction-Damped" condition involving $E_{D1} < 1.0$).



Figure 1: Full-scale two-bay, two-story pallet rack test specimen mounted on the AUT uniaxial shaking table with loaded pallets (1200 kg each), foundation blocks, and safety catch frame

Ancillary equipment, including a forklift and a bulk bag lifter, was used during assembly. For safety, an independent “Catch Frame” made of steel columns and links was installed around the test specimen to prevent catastrophic collapse. The complete test setup is shown in Figure 1.

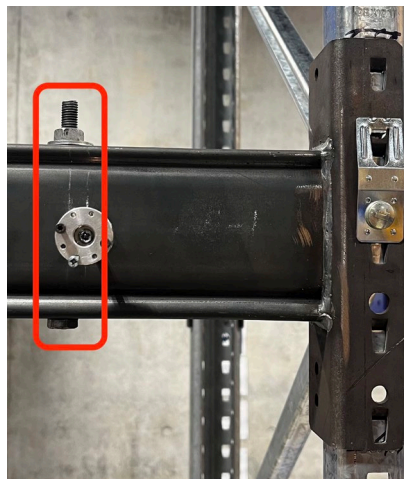


Figure 2: Detail of the bolt fastened to the beam to prevent pallet movement

The foundation system was designed to simulate a typical warehouse floor slab. It consisted of three 30 MPa reinforced concrete blocks, 100mm thick, with SE82 reinforcement, rigidly fastened to the shaking table platform.

2.2 Test Setup, Instrumentation and Data Acquisition Plan

The tests were conducted in the Structural Test Hall at the Auckland University of Technology (AUT) using its uniaxial shaking table. A comprehensive instrumentation plan was implemented to capture key dynamic response parameters using a synchronised Data Acquisition System (DAS). The sensor layout included 8 accelerometers, three displacement transducers, 22 portal gauges, and 4 cameras.

2.3 Ground Motion Selection and Loading Protocol

Three historical earthquake records were selected for the tests: Kobe (1995), Northridge (1994), and Imperial Valley (1940, El-Centro). These time-history records are commonly used in shake-table testing of storage racks. An incremental loading protocol was employed, in which ground motions were scaled to progressively increasing intensity levels (design ratios) to observe damage accumulation and non-linear behaviour, extending to intensities significantly beyond the Ultimate Limit State (ULS), consistent with established experimental methodologies (Castiglioni et al. 2014).

Design intensity ratios were evaluated in accordance with both NZS 1170.5:2004 (Standards New Zealand, 2024) and SNZ TS 1170.5:2025 (Standards New Zealand, 2025). The latter was included to reflect the increased seismic hazard demands associated with higher hazard factors and updated provisions in the forthcoming standard, thereby enabling assessment of system performance under more stringent seismic requirements. The specific loading regime adopted for the tested systems is summarised in Table 2.

Table 2: Shaking-Table Loading Sequence

Test Order	PGA (g)	Ratio of design level ULS to NZS 1170.5:2004	Ratio of design level ULS to SNZ TS 1170.5:2025	Ground Motion
1a	0.08	0.25	0.17	Kobe - 1992
1b	0.16	0.50	0.35	Kobe - 1993
1c	0.23	0.75	0.52	Kobe - 1994
1	0.31	1.00	0.69	Kobe - 1995
2	0.34	1.00	0.69	Imperial Valley - El Centro - 1940
3	0.35	1.00	0.69	Northridge - 01 - 1994
4	0.45	1.45	1.00	Kobe - 1995
5	0.52	1.50	1.03	Northridge - 01 - 1994
6	0.54	1.75	1.20	Kobe - 1995
7	0.62	1.76	1.21	Imperial Valley - El Centro - 1940
8	0.66	1.92	1.32	Northridge - 01 - 1994

The results of this comprehensive experimental program are presented and analysed in the following section.

2.4 Experimental Results and Analysis

This section presents the key quantitative and qualitative findings from the shaking-table tests.

2.5 Observed Physical Damage

The primary failure mode observed was cracking at the welded beam-to-upright connections, consistent with component failure mechanisms reported by Bové et al. (2023). Visual inspection in Figure 3 illustrates the progressive accumulation of damage with increasing seismic intensity. The connections were initially undamaged, but early cyclic loading caused crack initiation at the weld toe due to stress concentrations, ultimately leading to increased cracking between the weld and the beam and partial weld failure in some connections.

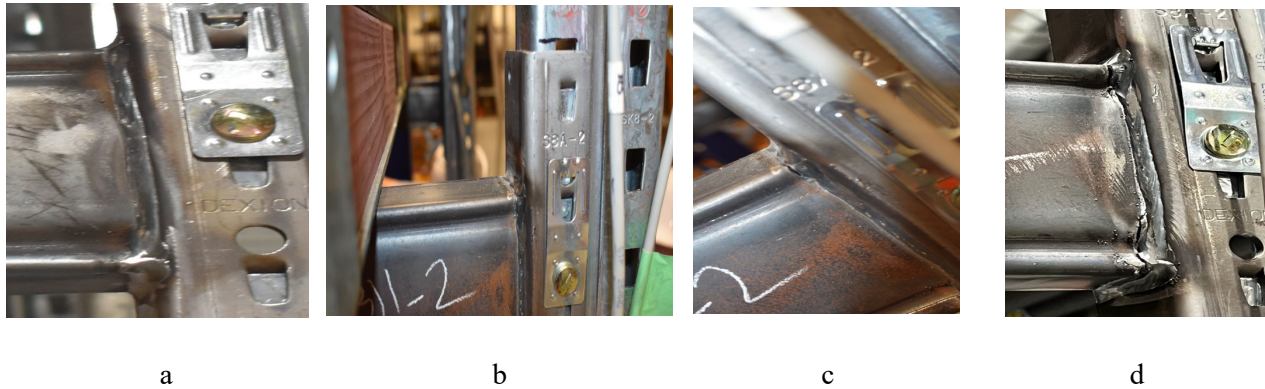
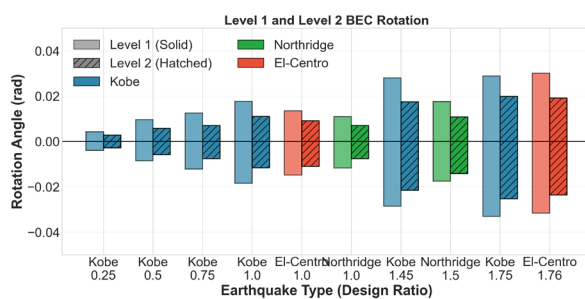


Figure 3: Progressive damage at beam-end connector weld: (a) Intact baseline condition; (b) Condition after El-Centro test No. 2 ; (c) Initial crack formation (6 mm) after Kobe test No. 4 (ratio 1.0); (d) Severe weld fracture (38 mm) after final El-Centro test. 7 (ratio 1.76).

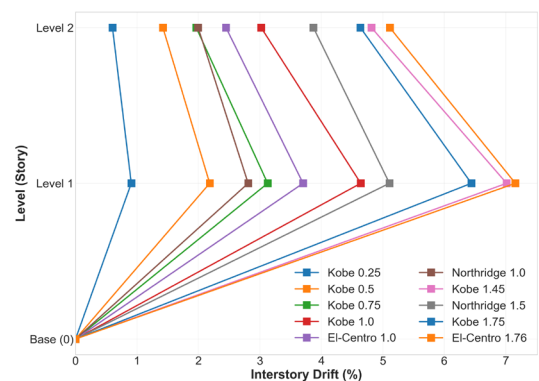
2.6 Seismic Response of the 90H Upright System

The 90H upright system exhibited stable, nonlinear behaviour, with progressively increasing deformation under increasing seismic demand.

- **Connection Rotation and inter-level drift:** The maximum rotation at the beam-upright connections increased with seismic intensity. Rotational demand at Level 1 was consistently greater than at Level 2 (see Figure 4-a). The drift at Level 1 was significantly higher than at Level 2 throughout the entire test sequence (Figure 4-b)



(a)



(b)

Figure 4: maximum a) beam-upright connection rotation, and b) inter-story drift for 90H system.

- **Acceleration:** A pronounced amplification of acceleration was recorded, increasing with the height of the structure (Figure 5), with a peak acceleration of 1.10 g during (Kobe 1.45), imposing high inertial forces on the stored goods.

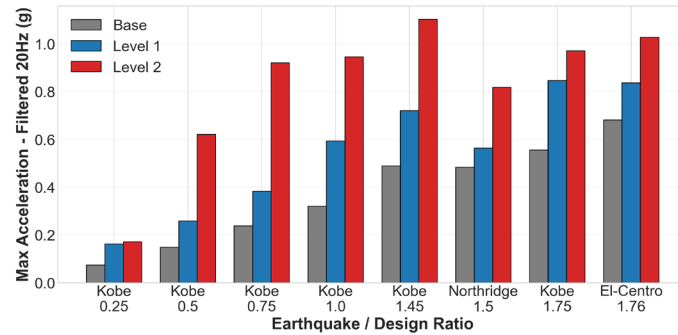
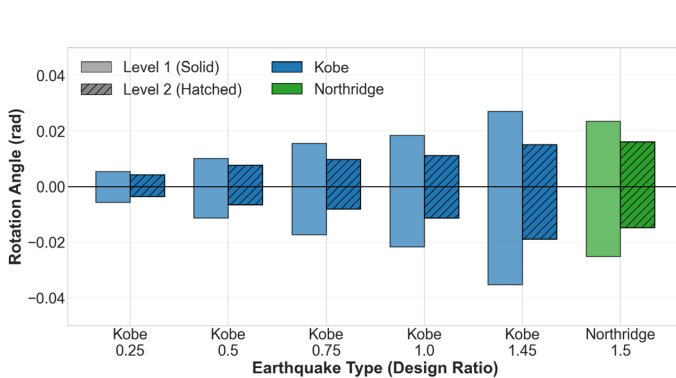


Figure 5: peak acceleration response for 90H system.

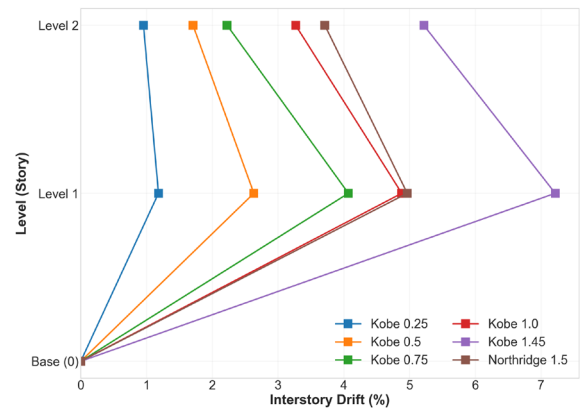
2.8 Seismic Response of the 90M Upright System

The 90M upright system showed similar behavioural trends, although its test sequence was terminated at a lower overall seismic intensity (Northridge 1.5) due to safety limits of the test facility.

- **Connection Rotation and inter-level drift:** Rotation increased with seismic intensity, with Level 1 demand consistently exceeding Level 2 (Figure 6-a), with a maximum of around 0.03. The trend of increasing drift with seismic intensity was clear, with Level 1 drift exceeding Level 2 drift (Figure 6-b).



(a)



(b)

Figure 6: maximum beam-upright a) connection rotation, and b) inter-story drift for 90M system.

- **Acceleration:** Significant amplification was also observed in this system (Figure 7). During the Kobe (1.45) test, a base input of 0.29 g was amplified to 0.84 g at Level 1 and 0.91 g at Level 2, representing an amplification factor of 3.1 at the top level.

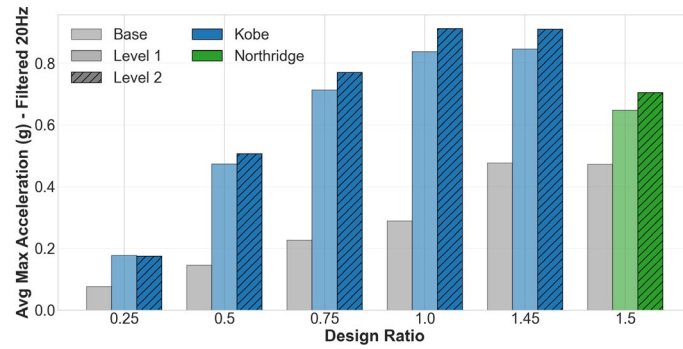
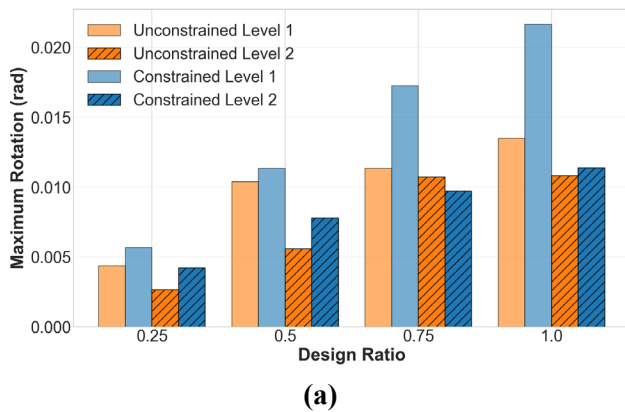


Figure 7: peak acceleration response for 90M system.

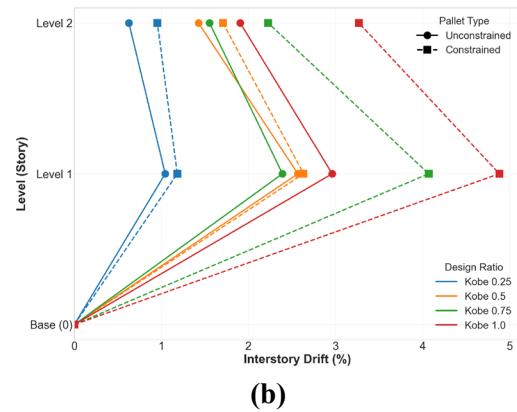
2.9 Comparative Analysis of System Performance and pallet load configuration

A comparative assessment demonstrates the superior seismic performance of the 90H system relative to the 90M system. At equivalent intensity levels, the 90M system exhibited greater elastic flexibility, with 11% higher Level 1 drift under the Kobe 1.0 motion compared to the 90H system, as shown in Figures 4-b and 6-b. This confirms that the enhanced section properties of the 90H uprights increased lateral stiffness and reduced drift demand. Although the 90H system reached higher absolute connection rotations, these occurred only during MCE-level tests, whereas the 90M system did not experience them. At equivalent intensities, the 90H system consistently exhibited lower rotations due to reduced frame sway.

A supplementary comparison between Unconstrained and Constrained pallet configurations validates the separation of friction damping E_{D1} and mass flexibility E_{D2} in EN 16681 (European Committee for Standardization 2016). At the Kobe 1.0 design level, the Constrained configuration resulted in up to 62% higher drift and rotation demands (Figure a-b). However, at higher intensities Kobe 0.75 and 1.0, the Unconstrained configuration exhibited higher peak accelerations. This inversion is attributed to the hammering effect, in which sliding pallets impact beams or uprights, generating high-frequency acceleration spikes despite reduced base shear and displacement. Figure 8 further shows that increased internal pallet movement contributed to energy dissipation but adversely affected stored goods.



(a)



(b)

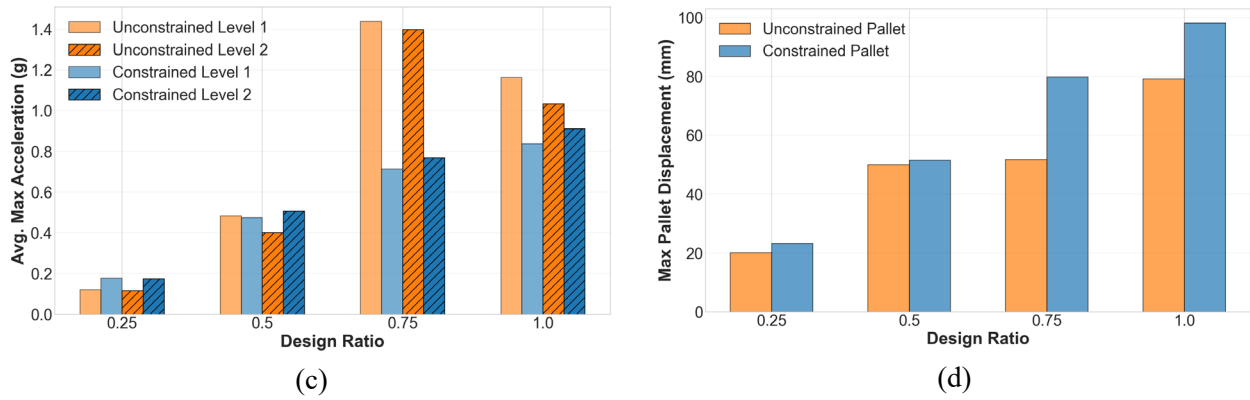


Figure 8: Comparison of a) connection rotation, b) inter-level drift, c) acceleration, and d) pallet displacement for unconstrained and constrained configurations.

3 DISCUSSION

This section interprets the experimental findings, connects them to fundamental principles of structural mechanics, and evaluates their implications for seismic design standards and industry practice.

3.1 Interpretation of System Behaviour and Performance Limits

The experimental results clarify the seismic response of the racking systems across increasing intensity levels. Moment rotation analysis indicates essentially elastic behaviour for rotations below 0.05 radians, suggesting satisfactory performance under design-level ground motions prescribed by NZS 1170.5 (Standards New Zealand 2004). Nonlinear response was observed only at elevated intensities up to 1.75 times the design motion, without significant stiffness degradation. The 90H system achieved a peak global drift of approximately 7.5% at Level 1 under extreme loading of 1.92 times the design level, exceeding typical ULS drift limits but remaining stable. This demonstrates substantial ductility reserve and collapse-prevention capacity, challenging assumptions of brittle behaviour and confirming resilience under Maximum Considered Earthquake demands. The drift-dominated response aligns with previous experimental findings (Kanyilmaz and Castiglioni 2017) and highlights the importance of second-order P Delta effects in these flexible pallet racking systems in the down-aisle direction.

3.3 Implications for Design Codes and Practice

The experimental findings on pallet load configuration provide clear physical validation for the separation of mass and damping effects in modern codes. Specifically, the comparison between Constrained and Unconstrained configurations directly validates the concept of the Pallet Friction Damping Factor (E_{D1}) introduced in EN 16681 (European Committee for Standardization 2016).

- Constrained ($E_{D1} \approx 1.0$): The system behaves as a fully coupled, rigid mass system, leading to higher base shear and drift demand. This confirms that mechanically fixing pallets, while preventing falls, imposes the maximum seismic load on the structure.
- Unconstrained ($E_{D1} < 1.0$): Allowing sliding acts as a friction-based isolation mechanism, significantly reducing structural drift.

However, the results also highlight a critical trade-off not fully addressed by the simple reduction factor E_{D1} : the "Unconstrained" configuration generated higher peak accelerations due to dynamic impact. This suggests that while E_{D1} appropriately reduces structural design forces, it should not imply a reduction in the safety requirements for the unit loads themselves.

4 CONCLUSIONS

Based on the experimental investigation and analysis, the following principal conclusions are drawn:

- 1- The 90H system with 2.5 mm thickness demonstrated superior seismic resilience compared to the 90M (2.0 mm) system, with lower inter-story drift and connection rotation at equivalent seismic intensities, thereby delaying damage initiation.
- 2- Unit load configuration significantly influenced seismic response, with the Constrained configuration producing over 62% higher inter-story drift and connection rotation demands, validating friction-based reduction factors such as E_{DI} in EN 16681.
- 3- Although Unconstrained pallets reduced global structural deformation, they generated higher peak accelerations at high seismic intensities due to pallet beam-induced impacts of very short duration (0.02-0.1s), indicating a trade-off between reduced structural demand and increased damage risk to acceleration-sensitive goods.
- 4- The racking systems maintained global stability at drift ratios up to 7.5% under seismic demands approaching twice the design intensity, demonstrating a substantial ductility beyond the elastic range.

This investigation underscores the value of full-scale experimental testing for validating design assumptions, understanding complex non-linear behaviour, and ultimately improving the safety and resilience of industrial storage systems.

Acknowledgement

The authors gratefully acknowledge the financial and technical support provided by **Callaghan Innovation** and **Dexion Group**; these contributions were instrumental in enabling the design, construction, and execution of the full-scale shake table testing programme. The authors also sincerely thank **Mr Lim Chern Kuang** for his constructive advice during the development of the experimental testing setup, which significantly enhanced the robustness and effectiveness of the experimental program.

5 REFERENCES

- Bové O, Casafont M, Bonada J, Ferrer M and López-Almansa F (2022). “Ductility improvement of adjustable pallet rack speed-lock connections”. *Journal of Constructional Steel Research*, 188: 107015. <https://doi.org/10.1016/j.jcsr.2021.107015>
- Bové O, Casafont M, Bonada J, Ferrer M and López-Almansa F (2023). “Investigation on the down-aisle ductility of multiple bay pallet racks through experimental tests and advanced numerical models”. *Engineering Structures*, 286: 116085. <https://doi.org/10.1016/j.engstruct.2023.116085>
- Castiglioni CA (2014). Seismic behaviour of steel storage pallet racking systems. Final Report EUR 27583 EN, European Commission, Research Fund for Coal and Steel, Brussels.
- European Committee for Standardization (CEN) (2016). “EN 16681: steel static storage systems – adjustable pallet racking systems – principles for seismic design”. CEN, Brussels, Belgium.
- Firouzianhaji A, Usefi N, Samali B and Mehrabi P (2021). “Shake table testing of standard cold-formed steel storage rack”. *Applied Sciences*, 11(4): 1821. <https://doi.org/10.3390/app11041821>
- Housner GW (1956). “Limit design of structures to resist earthquakes”. *Proceedings of the World Conference on Earthquake Engineering*, Berkeley, USA, Paper No. 6.

- Kanyilmaz A and Castiglioni CA (2017). “Experimental assessment of the seismic behavior of unbraced steel storage pallet racks”. *Engineering Structures*, 131: 449–466. <https://doi.org/10.1016/j.engstruct.2016.11.063>
- Peterman KD, Stehman MJ, Madsen RL, Buonopane SG, Nakata N and Schafer BW (2016). “Experimental seismic response of a full-scale cold-formed steel-framed building. i: system-level response”. *Journal of Structural Engineering*, 142(12): 04016127. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001585](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001585)
- Standards New Zealand (2004). “NZS 1170.5: structural design actions – part 5: earthquake actions – new zealand”. Standards New Zealand, Wellington, New Zealand, 76pp. <https://www.standards.govt.nz/sponsored-standards/building-standards/NZS1170-5>
- Standards New Zealand (2025). “SNZ TS 1170.5: structural design actions – part 5: earthquake actions – new zealand (draft technical specification)”. Public Comment Draft, Standards New Zealand, Wellington, New Zealand. https://consultations.standards.govt.nz/draft-standards/ts1170-5-public-consultation/user_uploads/20240215-ts-1170.5---public-comment-draft_v2.pdf
- Taghavi S and Miranda E (2003). “Response assessment of nonstructural building elements”. PEER Report 2003/05, Pacific Earthquake Engineering Research Center, University of California, Berkeley.