

# OBSERVED PERFORMANCE OF INDUSTRIAL PALLET RACK STORAGE SYSTEMS IN THE CANTERBURY EARTHQUAKES

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## SUMMARY

In Christchurch, the industrial sectors with storage facilities incurred heavy economic loss due to the collapse of pallet rack systems and loss of contents during the recent the Darfield (2010) and Lyttleton (2011) earthquakes. The failure of such systems could be attributed to various reasons including inadequate design, inappropriate operational conditions, improper installation and lack of maintenance. This paper describes possible sources of damage in pallet racks due to earthquake action, which eventually could trigger the collapse failure mode of the storage system during a severe aftershock.

Various racking manufacturers and retail owners were consulted to establish the pre-event condition and loading of the systems and the response of the systems in both 'publicly accessible' and 'industrial' situations. Investigations by the authors highlighted an apparent lack of consistent national control over the design and construction of racking systems. Progress towards the publication of a revised and extended Design Guide is also described.

## INTRODUCTION

A damage survey on industrial structures clearly indicated varied performance of steel pallet storage racking systems both in the Darfield (4<sup>th</sup> September, 2010) and Lyttleton (22<sup>nd</sup> February, 2011) earthquake events resulting in minimal to heavy economic loss. Storage racks generally fall under two categories: (i) racks in warehouses with public access where generally lighter contents are stored on upper level and heavier ones on the lower level racks and are with total height about 5 m; and (ii) racks in industrial facilities where heavy pallets are stored at all levels and the racks are often over 10 m high. A report on observations on the performance of racking systems after the Darfield event (Beattie and Uma, 2011) indicated that by and large the storage racking systems with light loading and public access, for example, in supermarkets, handyman stores and discount warehouses, did perform satisfactorily in both events. However, in industrial storage facilities, a large number of the heavily loaded and taller storage racks collapsed.

In New Zealand, design guidelines for industrial pallet racking systems were published by HERA in 1997 and in 1999. These no longer comply with current earthquake loading standards, NZS 1170.5. In 2007, BRANZ and the University of Canterbury produced *Design Recommendations for the Seismic Design of High Level Storage Racking Systems with Public Access* as a Design Guide (Beattie and Deam, 2007). The Guide is particularly applicable to supermarkets, home handyman stores and bulk retail outlet stores and was made available to the known racking system manufacturers and importers in NZ. The BRANZ document applies a height restriction of 5 m for the racks and recommends a design spectrum at a 250 year return period to represent only a 25 year design life. Since there is no standard updated document

for the design of industrial pallet racks, the designers are left with the choice of adopting the existing guidelines, which do include industrial pallet racks, or adapting American (BSSC 2005; RMI, 1997) or European references (FEM, 2010 ; Rossin *et al.*, 2009).

From field investigations, a number of earthquake induced damage mechanisms are identified. A thorough inspection is warranted to avoid failures and other unfavourable consequences. Pallet racking users need to be aware that these systems comprise high strength, heavily loaded, open sections with complex cross sections. Storage racks (frames) do not have the capability of remaining standing in a heavily damaged state, so it is important that damage in service and the design extent of controlled damage in a severe earthquake are kept to a minimum.

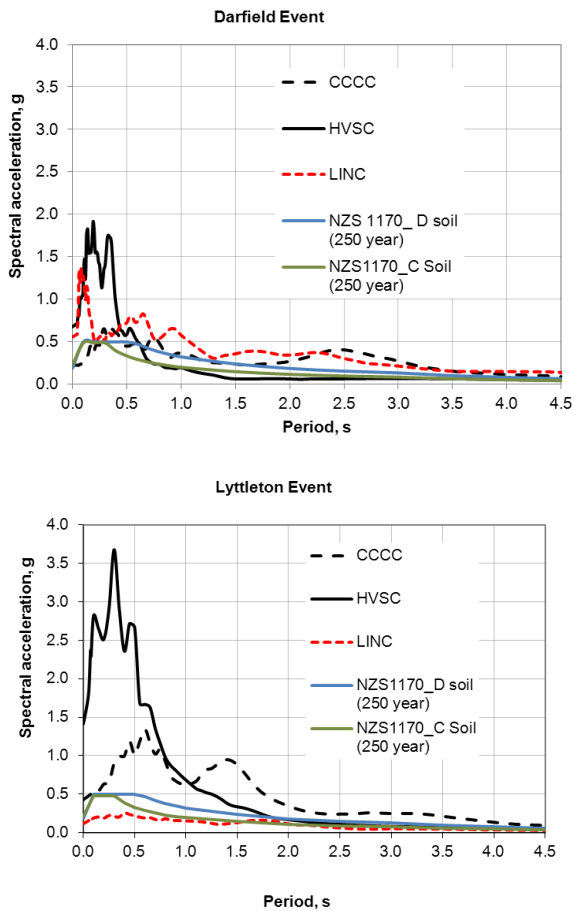
## GROUND MOTION SPECTRA

Ground motion characteristics from the Darfield event and the Lyttleton event are compared in Figure 1 in terms of response spectra plots for the ground motions recorded at 3 stations: (i) western suburbs – Lincoln; (ii) central zone – Cathedral college; (iii) eastern suburbs – Port Hills. The Lincoln and Cathedral college stations are in deep soil (class D) zone whereas Port Hills station is in shallow soil (class C) as per NZS 1170.5:2004. The recommended design spectrum for soil class C and D are plotted for a 250 year return period. In general, the period of tall industrial pallet rack system can range from about 1 second to more than 2 seconds. Considering the period range of interest, it is clear that in the Darfield event, the western suburbs closer to Lincoln exceeded the 'design' level spectrum than the eastern suburbs; whereas during the February event, racks in the eastern suburbs suffered collapse and the ones in the western suburbs survived

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without major damage. The central zone experienced ground motions closer to the design level in the Sept event and much higher during the February event. Many failures of racks near the Central zone were also reported. The impact of high vertical acceleration compared to the horizontal acceleration from both events added to the cause of failures.



**Figure 1:** Response spectra plots for ground motion at Cathedral College (CCCC), Port Hills (HVSC) and Lincoln (LINC) from the Darfield and Lyttelton earthquake events.

### CHANGE FOR CHRISTCHURCH SEISMICITY

The Darfield and the Lyttelton earthquakes have resulted in increased seismicity in the Canterbury region. Owners and operators should realise that if their racks are subjected to near fault action, collapse of a heavily loaded pallet racking system is a likely outcome. The Department of Building and Housing has provided an information sheet in the link <http://www.dbh.govt.nz/information-sheet-seismicity-changes>. The changes affect the Canterbury Earthquake Region only. In the Canterbury earthquake region, the risk factor for the serviceability limit has also been revised.

The effect on Pallet racks that were designed for a hazard factor,  $Z = 0.22$ , need to address the demands from increased seismicity. This can be achieved by: (i) checking the member capacity for the increased seismicity keeping the loads to be supported unchanged and redesign if necessary; or (ii) reducing the bay load to be supported and keeping the existing frame unaltered. The second option will indicate that the bay load needs to be reduced to match the increased seismicity. It is recommended that, if reduced loading is required, the top levels in the rack should preferably be loaded with a maximum of 80% of the revised design load, i.e. try to keep the major loads nearer to the bottom of the racks rather than the top.

### SEISMIC LOAD RESISTING SYSTEMS IN STORAGE RACKING

There are two main methods of resisting seismic loads in storage racking systems. These are:

- Moment resisting beam-column joints in the down-aisle direction, and
- Cross braced frames in the across-aisle direction



**Figure 2:** Typical pallet racking storage system (Photo: S.R. Uma).

#### DOWN-AISLE DIRECTION

The elemental nature of the racking system means that cross frames are erected and then beam elements are fitted between the frames to support the product loads. Hooks or tear-drop connections are utilised to make the joints between the beams and the frames, and once these are securely in place a moment connection results. In most racking systems, these moment resisting joints are the sole down-aisle seismic load resisting system. Sometimes, cross braced cables are installed in the vertical plane at the back of the rack (or in the middle between racks when racks are installed back to back) to supplement this system.

#### ACROSS-AISLE DIRECTION

The frames resisting across-aisle loads consist of two upright posts with cross bracing between. The cross bracing has several forms depending on the manufacturer. Some utilise horizontal and diagonal web members and some utilise all diagonal web members. There is further variation in the end fixings for these members. Some manufacturers bolt the webs to the upright posts using the available holes in the flanges of the posts and some weld the webs directly to the posts. Baseplate designs also vary. Some are welded directly to the posts and some are welded to short upstands, to which the upright posts are then bolted.

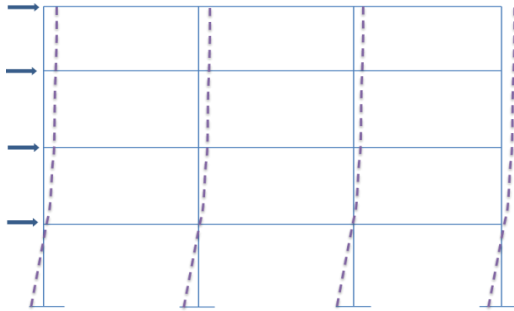
### POTENTIAL EARTHQUAKE INDUCED DAMAGE IDENTIFIERS

Due to severe earthquake actions close to or exceeding the design level, the rack members are likely to experience damage. Storage racking systems need to be inspected for their capacity to remain stable and to avoid failure of the system under a severe aftershock. Typical damage sources and patterns are described below:

1. **'Bow profile' in the upright columns in down-aisle direction.**

When the predominant earthquake loading is parallel to the down-aisle direction, the frame is subjected to lateral loads as shown in Figure 3. The upright members have remained

attached to the base plates and rotation at the beam/column connections could result in vertical out of plumb deflection and a deflected profile in the form of a 'bow'. The out-of-plumb damage is more likely to be visible at the bottom member than in the upright members in the upper levels.



**Figure 3:** Vertical out-of-plumb with bow effect in the upright members.

Also, out of plumb damage in upright members as shown in Figure 4 could result in possible twisting of the upright posts at bracing nodes and/or rotation of moment connections between the beams and the uprights.



**Figure 4:** Out-of-plumb in front and rear upright members.

**2. Damage in the beam connector elements**

The beam end connectors, safety clips and any other elements used to transfer beam moments are likely to suffer from any form of distress such as cracks in the parent metal, fractures in welds and possible loss of strength of connecting bolts (e.g. shear or bearing failure). Figures 5 to 8 illustrate possible failures in the beam connector elements.



**Figure 5:** Cracked/split at front of beam locating hook.



**Figure 6:** Beam end plate buckled.



**Figure 7:** Sheared off beam locating hook.



**Figure 8:** Damaged beam connector plate.



### 3. Damage to baseplates

Yielding and fracture of baseplates is a typical mode of failure. Sometimes down aisle shear forces at the baseplate twist the baseplate and the connected upright, as shown in Figure 9. An example of failure of the base plate connection is shown in Figure 10. Controlled yielding of the baseplate in a severe earthquake can be an intended mode of energy dissipation. In this case the baseplate should have been designed and tested for this mechanism and the manufacturer should be able to provide results for the testing. The specification for the tested baseplate should be available, so that the client can determine they have the same detail and materials. It is important that the baseplate is installed exactly as per the specification.



**Figure 9:** *Twisting of baseplate.*



**Figure 10:** *Failure of baseplate to upright post connection.*

### 4. Damage to bracing elements (across-aisle)

Figure 11 shows failure modes in the bracing elements. It is advisable to replace buckled braces and check carefully for cracks in the supporting connection into the column wall and locally in the column wall itself.



**Figure 11:** *Damaged diagonal bracing elements.*

Also, some systems use bracing wires to tie up the racks and the wires are anchored to the floor. These wires need to be checked to determine whether they have been stretched and if so need to be re-tightened or replaced. Their end connections to the rack or the floor may also be damaged.

### 5. Supplementary down-aisle bracing

Some systems use diagonal wires to brace the racks in the down-aisle direction and the wires are anchored to the floor. Due to severe earthquake actions, damage to their end connections to the rack and the floor is likely. Also, the wires tend to be over-stretched beyond their elastic limit and hence lose their ability to act as bracing elements.

### IMPACT OF THE RACKING AGAINST THE SURROUNDING BUILDING

Storage racking is invariably designed to be free-standing without support from the surrounding structure. It is important that seismic displacements of the racking can be accommodated without impacting on the building structure. Apparently there is at least one instance where parts of a rack have impacted the building structure as in Figure 12. In this case, fortunately the rack did not collapse as a result of the impact. However, such impacts could easily alter the response of the racking system to the earthquake motion and introduce unexpected loads on the system. They could also introduce unexpected load on the building, which could cause it to fail.



**Figure 12:** *Evidence of damage to a racking system from impact on the adjacent building structure.*

## USING SECOND HAND RACKING WITHOUT APPROPRIATE DESIGN CHECKS

The use of second hand racking introduces a potential for the creation of a weak system unless firstly the original manufacturer can be identified, secondly the properties of the sections are accurately established and thirdly a design check is undertaken on the proposed configuration. Without this process, there is a distinct possibility that the system may be overloaded under gravity loads or that it may be unable to resist design level earthquake loads expected at the new location. If the racking members do not satisfy the above requirements, they should be replaced with new ones. Damaged members should not be re-used under any circumstances and should be considered as scrap material.

## OPERATIONAL SAFETY CHECKS FOR RACKING SYSTEMS

Storage racking systems fall within the definition of 'buildings' in the 2004 (Building Act) and therefore must comply with New Zealand Building Code (NZBC) requirements. In particular, they must satisfy the provisions of Clause B1-Structure of the NZBC [Beattie and Deam, 2007].

The objective of Building Code clause **B1** is to:

- Safeguard people from injury caused by structural failure
- Safeguard people from loss of amenity caused by the way the structure behaves
- Protect other property from physical damage caused by structure failure.

Regular, detailed inspection of racking systems is highly recommended. A framework to practise the safety check guidelines should be in place within industrial storage facilities. Life-safety hazard is high for the employees due to the collapse of racks and falling of pallets. Managers should be aware that they are responsible for the safety of employees (Health and Safety in Employment Act 1992). Also it should be realised that failure of racking systems incurs heavy economic loss due to damage to contents and business interruption.

Some specific measures to be undertaken in identifying the damage under static conditions are included in AS 4084:1993 and the SEMA code of Practice for the Use of Static Pallet Racking- Clause 8.4 on Rack protection.

The "SEMA Code of Practice for the Use of Static Pallet Racking" gives general guidance for performing rack safety checks. Some of the recommendations from SEMA include:

- a check on safe-working loads on the bay
- maintenance of safety sign regulations
- alterations in racking systems to be performed under scrutiny
- safe-storage of pallets
- use of additional devices to prevent direct damage to the racks, and
- direct and immediate reporting of any damage or near miss occurrences to a supervisor.

Attention paid to the above points would help reduce the hazard or reduce the risk of rack collapse. If damage is sustained, the racking members should be condemned and replaced with new ones. Such damaged members should not be re-used under any circumstances and should be considered as scrap material.

## IMPLICATIONS OF THE CANTERBURY EVENTS FOR THE DESIGN GUIDE

The authors do not see any necessity to adjust the content of the Design Guide (Beattie and Deam, 2007) with respect to its application to the design of public access, high level, storage facilities. The performance of such systems in Christchurch was quite satisfactory in that in all but one or two minor cases of rack overloading, all racks survived the earthquakes. However, there are several initiatives undertaken to extend/modify the guide to include industrial storage racking systems. The primary initiative is to revisit the area reduction factor and the rigid mass factor. Currently the first of these factors is set at 0.8, which appears to be suitable for public access systems but too low for industrial systems where the racks tend to be much intensively loaded. The second factor takes account of potential sliding of rack contents in an earthquake. This factor is set at 0.67 at present in the Guide. Closely stored pallets containing closely packed and wrapped contents are not likely to have the space to slide and the magnitude of this factor may therefore not be relevant for industrial storage systems. In addition to the above two factors, discussions are underway to address a few more issues that relate to industrial storage facilities, including load combination factor, risk factor and the specified design life period. A critical review of the current Guide (Davidson and McBride, 2011) has supported the extension of the document to suit the design of industrial storage racking systems in New Zealand conditions. Supporting materials for pallet racking designs from overseas [FEM, 2010; Rossin et al., 2009] are available in the literature. In some cases, substantial experimental investigations have been carried out to demonstrate the performance of pallet rack systems in seismic conditions.

Observations of failures in this earthquake suggest that the inclusion of pallet support bars between the main down-aisle beams would serve to prevent fall through of pallets during an earthquake, and such recommendations are likely to be included in the revised Guide. Australian standard pallets have boards positioned in such a way that a mechanical connection can be relied on between the pallets and the racking. In this case, support bars are not necessary.

The authors have received a clear message that there is not enough regulatory control on the design and installation of storage racking systems, despite the presence of standards and guides. The principal reason for this is that there seems to be confusion about whether high level (including industrial) storage racking requires a Building Consent. The Department of Building and Housing (DBH) has advised that the racking system will need to comply with the functional requirements and performance criteria of the NZBC, as required by Section 17 of the Building Act. Territorial Authorities need to be made aware of this requirement when new and second hand storage racking systems are installed within their area of jurisdiction. The authors are members of the study group involving design engineers, racking manufacturers and suppliers, city council representatives, and DBH which is working to resolve various issues discussed within this paper.

## CONCLUSIONS AND RECOMMENDATIONS

The Darfield and Lyttleton earthquake events have resulted in an increased level of seismicity in the Canterbury region. This necessitates changes in the operational requirements of existing industrial pallet racking systems such as verification of member capacity of existing racks and reduction of the safe working load on the bays.

Potential earthquake damage identifiers in racking systems are discussed in this paper. Rack inspections need to be carried out to identify the presence of any such damage which could potentially lead to major adverse consequences in future events. Many industrial storage facilities have their own framework to perform verifications of the safety of pallet rack structures for static conditions. However, it is very important to have trained, competent rack safety personnel to perform detailed inspections to identify earthquake related damage in the event of large aftershocks. Under Occupational Safety and Health, the Department of Labour has covered all practical steps and it is the responsibility of employers to make sure that the working environment is safe at any time.

There is a significant risk involved in re-using the damaged materials for rack installation and therefore such materials need to be avoided under any circumstances.

It is recommended that professional training programmes be offered in New Zealand in order to improve the safety awareness of users of industrial storage racking systems.

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