

PERFORMANCE OF STEEL STORAGE RACKS IN THE DARFIELD EARTHQUAKE

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SUMMARY

The author inspected 18 racking installations at various food storage facilities in Christchurch for damage from the 4th September 2010 Darfield Earthquake. The type of racking installations and damage suffered are listed with some photographs of specific damage. The damage ranged from minor to complete collapse with large product loss. Although inspection access was limited, the collapse mechanism for racking installations is assessed and suggested. The damage inspected indicated some variation in the application of design approaches and potential areas where the behaviour of rack structures may not have been fully understood during design. General conclusions are drawn from the damage inspections, and suggestions offered for the refinement and improvement of racking design approaches.

INTRODUCTION

Damage to racking in food storage facilities in Christchurch during the 4th September 2010 Darfield earthquake resulted in product losses of several hundreds of millions of dollars. This paper is a summary of personal inspections and observations of damage caused to steel racking during the earthquake. In the four weeks immediately following the earthquake, the author undertook inspections for owners of 18 different racking installations in food and cold storage facilities. The racks were a variety of types of installation – selective, double-deep selective, drive-in, and satellite – and all but one were constructed from light gauge cold-formed steel sections, typical of New Zealand commercial racking. These racking installations suffered a range of damage from essentially undamaged right through to complete collapse with near-total loss of stored product.

Reported ground accelerations in Christchurch (1), where the racking collapses occurred, were between 0.17g to 0.23g – less than the 1/500 return period “design” earthquake, though this may vary depending on soil conditions. Earthquake induced racking damage inspected indicated several areas where design and loading assumptions may have shortcomings and/or be misunderstood or incorrectly applied by designers.

The paper is intended to be complementary to the paper *Damage to Steel Storage Racks in Industrial Buildings in the Darfield Earthquake* [2] published in the December 2010 edition of the NZSEE Bulletin, extending and expanding the observations in that paper, and adding the author’s suggestions for reviewing the procedures in existing New Zealand design guidelines for steel store racking.

BACKGROUND

Most racking structures in use in New Zealand, particularly in the food and cold storage industry, use light cold-formed steel sections for the main structural members. The installations have traditionally been designed by the racking manufacturers and erectors, using in-house or specialist consultant structural designers. Design has historically been based on the New Zealand loadings and structural steelwork design standards [3, 4], plus the Australian cold-formed steel structures standard [5]. As none of these standards specifically apply to New Zealand racking installations, designers traditionally made experience-based assumptions for loading cases, load diversity

and site application. The Heavy Engineering Research Association (HERA) has coordinated industry practice with the design standards to produce broad guidelines and recommendations for the design of cold formed steel racking [6, 7, & 8]. The initial 1983 publication [6] was general, but it was updated in 1995-99 [7, 8] to produce design recommendations and guidance notes on seismic design of racking structures, incorporating loading, design and material code requirements and with a basis for assessing racking loads. These have been widely used as a basis to consider racking design and are likely to have been the basis for design of most of the racking installation inspected and reported on in this paper. The guidelines were written around the then-loadings design standard NZS 4203:1992 [3], so need updating to NZS 1170.5:2004 [4] for the current seismic design approach.

In 2007, BRANZ produced a guideline for the design of selective racking systems in retail storage installations (ie. publically accessed racking installations) [9]. It has been specifically written as a design guide for selective racking, single and double-deep and is probably the most appropriate guide available at present for the seismic design of this type of racking in New Zealand. Curiously, it appears the BRANZ guideline was written without reference to the HERA design guides.

Some non-New Zealand racking designers appear to use overseas seismic design bases, but the author thinks these guidelines are inappropriate for use in New Zealand design without detailed assessment. The standards are unlikely to comply with the NZ Building Code Verification Method or Acceptable Solution designs, and seismicity factors for overseas design standards may not be related to New Zealand conditions.

Although there has historically been variation around New Zealand in Building Consent Authorities’ requirement for building consents for racking installations, racking structures are “buildings” in terms of the Building Act [12] so should have a building consent before they are erected. The racking should be specifically designed for the storage environment treated as a building structure, and have a building consent, not be regarded as a mechanical plant item. The design basis and compliance will be determined by product loading and handling requirements, but seismic loadings should be considered in accordance with either the BRANZ [9] or HERA design guidelines [7, 8].

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Post-earthquake observations of damaged racking

PHOTOGRAPHS OF RACKING DAMAGE



No.1 Single deep selective racking.



No.1 Single deep selective racking.



No.1 Beam/column joint in above.



No.1 Clip beam/column joint in above.



No.3 Single deep selective racking.



No.3 Single deep selective racking.

Table 1: Post-earthquake observations of damaged racking									
No.	type	height (No.pallets)	Product	est'd pallet weight	% loaded at E/Q	Orientation	estimated year of installation	Nature of E/Q damage	
1	single deep selective	4 pallets	pallets of bagged flour	1 tonne	100%	facing both E-W & N-S	mid 1990s	sway collapse down-rack, rotation of end frames and progressive collapse	
2	single deep selective	3 pallets	pallets of carton blanks	600 kg	100%	pallet faces E-W	early 2000s	no damage or deflection	
3	single deep selective	4 pallets	pallets of cartoned consumer dairy products	1 tonne	80%	facing both E-W & N-S	mid-late 1990s	rotation of end frames and progressive collapse	
4	drive in - 6 deep	4 pallets	pallets of cartoned milk	1 tonne	70%	drive in from E & W	mid-late 1990s	lateral sway collapse; lateral deflection rack columns allowing pallets to drop	
5	single deep selective	6 pallets	FMCG supermarket goods	850 kg	95%	pallet faces N-S	1991	rotation of end frames - 75% progressive collapse	
6	single deep selective	6 pallets	FMCG supermarket goods	850 kg	95%	pallet faces N-S	1991	rotation of end frames - 75% progressive collapse	
7	single deep selective	6 pallets	FMCG supermarket goods	850 kg	95%	pallet faces N-S	1991	rotation of end frames - 75% progressive collapse	
8	single deep selective	6 pallets	FMCG supermarket goods	850 kg	95%	pallet faces N-S	1996	damage to b/plates & verticals, less than 5% lateral instability	
9	drive-in 9 deep	3 pallets	Cartoned cheese	850 kg	50%	drive in from N	late 1990s (re-erected)	minor lateral sway, lateral deflection rack columns allowing pallets to drop	
10	drive-in 9 deep	4 pallets	Cartoned cheese	850 kg	15%	drive in from N	late 1990s (re-erected, non- standard col altns)	no damage or deflection	
11	post pallets	3 pallets	cartoned frozen meat	1 tonne	100%	stacked on top of each other	1980s	lateral sway collapse	
12	double deep selective	5 pallets	cartoned frozen meat	1 tonne	100%	drive in from E & W	early 1990s	lateral sway collapse	
13	single deep selective	5 pallets	FMCG supermarket goods	1 tonne	90%	pallet faces N-S	early-mid 1990s	sway collapse down-rack, rotation of end frames and progressive collapse	
14	single deep selective	5 pallets	FMCG supermarket goods	1 tonne	90%	pallet faces N-S	early-mid 1990s	sway collapse down-rack, rotation of end frames and progressive collapse	
15	single deep selective	5 pallets	FMCG supermarket goods	1 tonne	90%	pallet faces N-S	early-mid 1990s	sway collapse down-rack, rotation of end frames and progressive collapse	
16	drive-in 11 deep	4 pallets	Cartoned cheese	850 kg	45%	drive in from E & W	2009 (re-erected)	lateral sway collapse; lateral deflection rack column allowing pallets to drop	
17	double deep selective	5 pallets	cartoned frozen poultry	850 kg	95%	drive-in from N-S	2002	sway collapse down-rack, rotation of end frames and progressive collapse	
18	satellite racking approx 8 deep	4 pallets	bulk bins & cartoned frozen vegetables	1 - 1.5 tonne	85%	pallets face E-W	2009	no damage or deflection	

PHOTOGRAPHS OF RACKING DAMAGE continued:



No.4 Drive-in racking.



No.4 Drive-in racking.



No.4 Eccentric & inadequate X bracing to drive in racking.



No.5 Single deep selective racking.



No.5 Single deep selective racking.



No.5 Single deep selective racking columns.



No.8 *Single deep selective racking.*



No.8 *Baseplate yielding to racking columns.*



No.8 *Baseplate & brace yielding to columns.*



No.9 *Distorted bracing to drive-in racking.*



No.9 Deflected columns to drive-in racking.



No.9 Forklift damaged columns.



No.11 Distorted post pallets.



No.12 Double deep selective racking.



No.12 Distorted double deep racking beam/column.



No.12 Wall pounding of double deep selective racking.



No.13 Single deep selective racking.



No.16 Deflected columns to drive-in racking.



No.16 Deflected columns to drive-in racking.



No.16 Collapsed drive-in racking.



No.17 Collapsed double deep racking.



No.17 Collapsed drive-in racking.



No.17 Wall pounding from collapsed racking.



No.17 Roof prop impact from collapsed racking.

OBSERVATIONS

As is evident from the photographs, much of the badly damaged racking was in an unsafe state immediately after the earthquake so inspection was from a distance in those installations, and necessarily cursory. Although the author was not able to investigate the failures of the various racking installations in close detail because of safety issues, the general issues observed, and considered to have contributed to the failures, are as below. The author inspected two of the less damaged installations – Nos.8 and 9 - in detail.

General observations from the racking damage were:

Selective Racking

- There were excessive lateral deflections of selective racking structures during the earthquake, particularly in the longitudinal direction when the racks were only framed, with no longitudinal cross bracing, which appeared to have led to apparent instability of columns from P-delta effects. This appeared to have been the major contributing factor to racking collapses.
- In three and four pallet high installations, racking was unstable when only framed in down-rack directions – bracing is necessary for seismic stability with the cold formed sections commonly used.

- On some of the older racking, the diagonal bracing to column pairs in the short frame direction was potentially unstable with thin cold rolled angle sections with unstiffened legs (*ie.no lips on the angles*). These appeared to have a much lower capacity than required and failed by axial buckling – a brittle manner - leading to excessive deflections of the structure and collapse.
- The different frequencies of short period cross frame response and longer period down-frame response appear to have contributed to some out-of plane deflection, leading to a twisting, curling mode of collapse. This also appeared to have occurred in some drive-in racking installations.
- The damaged and collapsed racking was in a variety of orientations – there was no clear predominant direction to the collapse.
- Detailed investigation of installation No.8 selective racking indicated no capacity design measures were used for baseplates – cold rolled column section welding to the baseplate was not continuous so local buckling occurred with and without baseplate bending.

Drive-in Racking

- Incomplete load paths existed in some racking installations, where load paths for horizontal cable

cross bracing in the top plane of the racking to vertical column pair bracing were not continuous and relied on bending in cold rolled column sections. The buckling failure of sections under bending appears to have led to sway failure and collapse of racking blocks.

- In drive in racking which was not fully loaded, columns deflected laterally, allowing pallets to drop down between the support rails.
- In fully loaded drive-in racking there was widespread failure laterally, apparently due to excessive deflection and P-delta effects as described above.

Satellite Racking

- The one satellite racking installation inspected appeared to confirm the significant added stability provided by additional cross-beams which are installed at each pallet level in this type of racking.

Post pallets

- The one post pallet installation had no holding down fixings, and appeared to fail from both uplift of upper pallets from the lower, and lateral sway deflection of the pallet uprights. Post pallets were initially designed in the early 1970s and have traditionally been limited to three pallet high stacking. The author's subsequent checking of similar post pallets for a temporary post-earthquake installation confirmed the requirement for holding-down fixing for stability, and the potential instability of post pallets when stacked more than three high.

General comments

- In several cold store racking installations, racking had pounded against cold store walls. This appeared to be due to excessive racking deflection as the building structures generally showed little evidence of lateral movement in the earthquake, and the racks were partially collapsed and in places held up by the cold store walls.
- Damaged racking components appear to have contributed to racking collapses in some cases, though this damage does not appear to have been the primary cause of collapse.
- There was no visible damage to concrete floor slabs in any of the installations, apart from local chipping and impact damage from collapsed racking and product. There were some pull-out failures of expansive fixing bolts from concrete slabs, but no evidence of slab cracking from either uplift or downward loadings.

The majority of the racking installations inspected were on relatively sound, deep, sandy gravel/silty sand foundation material typical of Canterbury foundations, with the water table at least 2 m below slab bearing level. None of the racking installations were close to any areas of notable liquefaction. Only one installation – No.1 – was near known areas of soft subsoils, but there was no evidence of any settlement or excessive movement of the warehouse floor where the racking was installed. The soils would all initially be classified as Class D, deep or soft soils for seismic load assessment to NZS1170.5, though shear wave testing may alter that classification to nearer Class C, shallow soil.

CODES/DESIGN GUIDES USED FOR RACKING PRIOR TO THE EARTHQUAKE

The author expects the design guidelines used for the design of the racking were likely to have been:

- For most of the racking designed after the mid 1990s – NZS 4203:1992 [2] for loadings, using the HERA bulletins Nos. 31 [7] and 53 [8], NZS 3404:1992 and AS 4600 [5] and fore-runners – ie.it is expected NZ design guidelines and standards were generally used
- For racking prior to the mid 1990s – NZS 4203:1992 [2] or NZS 4203 1984, plus the HERA 1983 guideline [6], and the forerunners of AS 4600 [5].
- None of the racking installations inspected are likely to have been designed to BRANZ guidelines.
- It is likely many of the racking installations were installed without a building. consent.

It is likely only the almost undamaged 2009 satellite racking installation (*No.18*) was designed for seismic loads to NZS 1170.5:2004 [3].

RELEVANT CURRENT DESIGN STANDARDS

The relevant current design standards used for racking design in New Zealand are generally as outlined above:

- AS/NZS 1170 – Structural Design Actions, particularly NZS 1170.5:2004 – Structural Actions, Part 5: Earthquake Actions [4].
- BRANZ Seismic Design of High Level Storage Racking Systems with Public Access [9].
- AS/NZS 4600:1996 – Cold Formed Steel Structures Standard [5].
- NZS 3404: 1997 - Steel Structures Standard - as applicable (ie. for plate sizes thicker than 5 mm) [13].
- AS 4084:1993 Steel Storage Racking Standard (for general guidance)
- Recommendations of the Heavy Engineering Research Association (HERA) for the Design of Pallet Racking Systems, including provisions in the following HERA Design and Construction Bulletins No.31, April 1997 and No.53, December 1999 (*these are written around the now-superseded NZS 4203:1992 Loading Code [3]so are not up-to-date*).

CONCLUSIONS

Based on these observations, and without any detailed analysis, the author's initial conclusions regarding racking seismic design are noted below.

- Unless detailed soil analysis is undertaken, for Christchurch racking installations, seismic load analysis to NZS 1170.5:2004 [4] should be based on Class D deep or soft soils.
- As most cold store operators aim to achieve 90% to 95% racking utilization, large areas of racking will often be at 100% loading. Hence any reduction for load diversity (*a procedure is suggested in the HERA design guidelines [7, 8]*) should be applied with caution. The author generally recommends design for all rack spaces full of design weight pallets for seismic weight assessment. An average pallet weight may be appropriate for installations where there is wide product and pallet weight diversity.

- The lightweight cold rolled steel section racks are short period structures, particularly in the cross-frame direction, when unloaded. When the racking is loaded, the structures become a long-period structure in both directions so attract less seismic load for the equivalent static design basis. Loading analysis to NZS1170.5:2004 [4] should make a spectral assessment – to a reasonable extent – for the variation in period which may occur with a range of partially loaded racking up to 100% loading.
- As cold formed steel sections in racking structures do not fail in a ductile manner, the racking structures must be designed for elastic response or at least no higher ductility than μ of 1.25.
- If baseplate yielding is designed for, capacity design must be applied to the cold rolled columns and bracing connected to the baseplate. It did not appear this approach had been taken on any of the racking inspected by the author after the earthquake. With the thin 3 mm to 6 mm baseplates in the racking inspected, it is unlikely the baseplate yielding will produce sufficient energy absorption to be able to achieve any significant ductility. Thicker baseplates, at least 10 mm or more, are likely to be required, with associated over-strength problems connecting the light cold rolled column sections to these baseplates.
- If a nominally elastic response design approach with structural ductility of $\mu = 1.25$ is used (*the author expects most of the racking installations inspected were designed to $\mu = 1.25$*), then capacity design should be used where potentially brittle bracing elements are used, in accordance with the procedures and recommendations in NZS 3404:1997 [13].
- Selective racking, both single and double-deep must have bracing in the down rack direction to limit deflections, and this bracing should be connected at several levels of the racking. Excessive deflections, particularly at the end columns in racking rows, appear to be a critical point for initiation of collapse so the combined effect seismic deflections from both primary rack directions must be considered for rack stability and P-delta effects. On several of the failed selective racking installations, the bracing was only connected at the top rack level and floor for six pallet high installations.
- Racking design should also include consideration of in-plane diaphragm action to avoid torsion deflection at the rack beam levels. Loaded pallets would normally be considered to provide diaphragm action, but the collapses cast some doubt on how effective this may be. NZS 1170.5:2004 does not allow for friction being beneficial under earthquake loading because of vertical acceleration effects.
- Racking columns must be designed with sufficient lateral stiffness between support points to retain the product under earthquake loading, particularly drive-in racking with high laterally unrestrained columns.
- Consideration must be made in design and fabrication to allow for potential embrittlement at welds to the cold rolled racking sections, particularly in low temperature cold store installations.
- Racking should be designed with protection against forklift damage (*all racking manufacturers have standard protection components*) and racking should be inspected regularly to identify damaged racking components, and these replaced with new.

These conclusions suggest the HERA and BRANZ design guides should be reviewed, combined and updated to incorporate some of the apparent lessons to be learnt from the Darfield Earthquake effects.

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