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A Revised Guide for the Design, Construction and Operation of High Level Storage Racking Systems following the Darfield Earthquake

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ABSTRACT:

In 2006, 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. 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. During the Darfield earthquake, it appeared that racking systems in these operations generally behaved satisfactorily. However, there were anecdotal reports that several industrial storage racking systems had failed resulting in multi-million dollar losses from damaged product stored on these systems, with the racking systems themselves needing to be completely replaced.

This paper describes an investigation of both the behaviour of systems that reportedly performed well and the failure mechanisms of those that did not. 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 'public 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 Guide is also described.

1 INTRODUCTION

In 2007, following experimental investigations and searching of overseas literature, BRANZ and the University of Canterbury published recommendations for the design of high level storage racking in areas with public access. These recommendations were reviewed by Spencer Holmes Ltd and at the request of the Department of Building and Housing, the recommendations were rearranged and published as the Design Guide *Seismic Design of High Level Storage Racking Systems with Public Access* (Beattie & Deam, 2007). The Guide contained information on regulatory requirements, applicable standards, loads, analysis procedures and recommendations for store operators with regard to the operation of their racking systems. The last section of the document recommended a process for store operators to inspect their racking systems after an earthquake. The Guide focused, as the name suggests, on the types of racking system that would be found in supermarkets, home handyman stores and discount warehouses.

The Darfield earthquake of 4 September 2010, tested all racking systems in the Christchurch area. BRANZ and GNS Science considered that the experience of the earthquake would provide an ideal opportunity to verify or amend the Guide and also to extend the Guide to cover industrial storage racking systems with no public access.

2 OBSERVATIONS IMMEDIATELY FOLLOWING THE DARFIELD EARTHQUAKE

2.1 Supermarkets

Immediately after the earthquake, supermarkets with high level storage racking remained closed. This was also the case in supermarkets with low level shelving systems because of large stock losses from shelves and the need to clean up the damaged stock. Observations suggest that racking systems from a range of manufacturers are used in supermarkets. The authors are not aware of any racking failures in these stores.

2.2 Home Handyman Stores

Home handyman stores pack their shelves similarly to supermarkets because of the need for the public to pick from the lower shelves. The principal difference between the two store types is the weight and size of the stored items. Handyman stores tend to have heavier individual items such as 10 litre paint pails and workshop tools. The details of the restraint systems for the rack contents on the upper shelves differ from one company to another but range from solid doors to mesh gates to ropes. However, there are still individual items stored in an unrestrained state on some of the upper shelves.

The authors have been unable so far to obtain any photographic or video evidence of the behaviour of racking systems in home handyman stores. However, two Christchurch store managers were interviewed within a month of the event (no reference because of confidentiality). In one instance, the manager related that two pails of paint had fallen from a shelf and the evidence of the cleaned up spilt paint was still on the floor at the time of the interview. The manager also noted that a few other small items fell. She also observed the rack behaviour first hand from her office window during the magnitude 5.1 aftershock on Wednesday 8 September. She described how the pallets on the top shelf of the racks in her store appeared to lift off the shelf and then translate towards the front of the shelf sufficient to cause her to have them repositioned.

The second store manager described a very similar performance to that of the first store manager during the main event. Five paint pails were spilt and some tall narrow sealant tubes also fell. This manager described relatively minor damage to the moment connections in their drive-through store. Management considered that this was sufficient to have the rack system dismantled and replaced in this area.

2.3 Discount Warehouses

It is understood that the racking systems in a major discount warehouse chain behaved well in the earthquake, but the authors have no first-hand knowledge and are not aware whether there was any stock loss from the shelves. It is also understood that this company uses the same racking supplier. It appears that a net system is used to prevent the loss of contents from the upper shelves of these racks in all their stores.

2.4 Commercial Warehouse Racking

Several failures of warehouse racking have been well publicised (e.g. Foodstuffs distribution warehouse) but unfortunately, there has been little opportunity to carefully analyse any of the collapses. The authors had limited opportunities to gather data first hand directly after the earthquake. When there was an opportunity, invariably the shambles of fallen stock has made it very difficult to conduct a forensic examination to make a definite call on the first reason for collapse. The authors observed examples of racks that had collapsed in the across-aisle direction and others that were severely distorted in the along-aisle direction. Further discussion of the observed failures is given later in the paper.

3 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

3.1 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 many 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.

3.2 Across-aisle direction

The frames resisting across-aisle loads consist of two 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 columns 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 posts are then bolted.

4 POSSIBLE REASONS FOR RACK FAILURE IN EARTHQUAKES

There are several potential reasons for failure of racking systems in earthquakes. These include:

- greater than design earthquake loads
- incorrect design of the racking members and connections
- poor manufacture of rack elements – welds, lugs
- unapproved alteration of the shelving configuration
- using second hand racking without appropriate design checks
- overloading of the racking by the store owner
- unrepaired damage caused prior to the earthquake (e.g. forklift impacts)
- impact of the racking against the surrounding building

Each of the above reasons is explored in more detail in the following sections, with reference to observed and notified behaviour.

4.1 Greater than design earthquake loads

Several Geonet (www.geonet.org.nz) strong motion seismographs were operational in the Christchurch area when the earthquake occurred. An analysis of these records has been undertaken by GNZ Science (John Zhao communication) and plots of acceleration spectra for the major principal direction are presented in Figure 1 (Riccarton High School) and Figure 2 (Rolleston School), along with design spectra from AS/NZS 1170.5 (SNZ, 2004).

The rack stiffness is generally similar between the across-aisle and down-aisle directions because the cross braced frames are tall cantilever frames with similar flexibilities to the moment-connected down-aisle frames. First mode periods for full racks are expected to be greater than 1 second. Inspection of Figures 1 and 2 indicates that the recorded earthquake was very likely to have been greater than the design level earthquake.

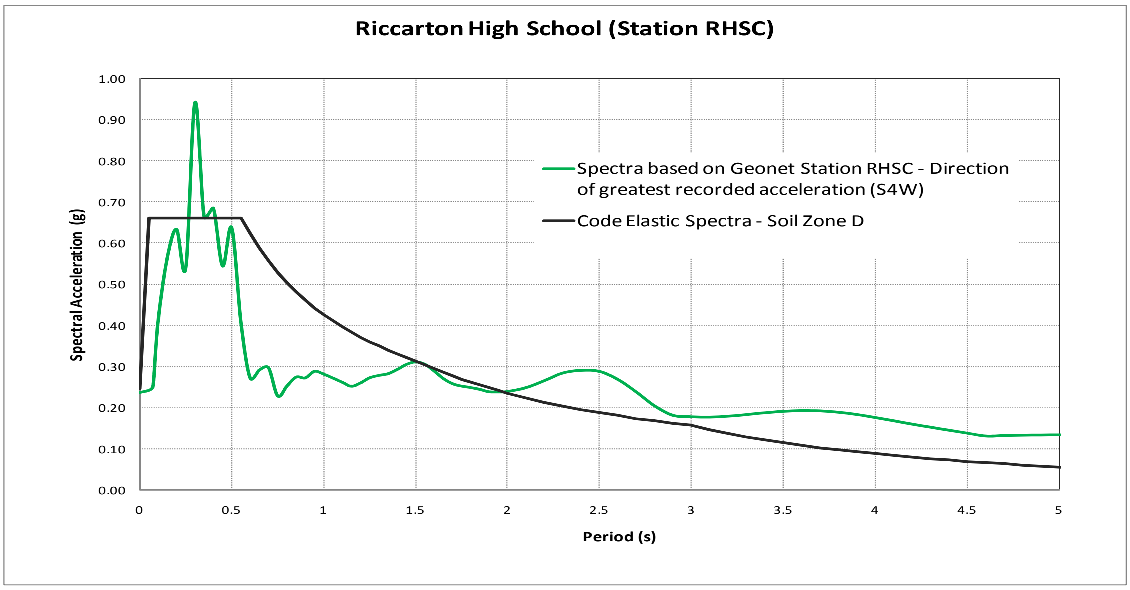

Figure 1 Acceleration response spectra for the S4W direction recorder at Riccarton High School

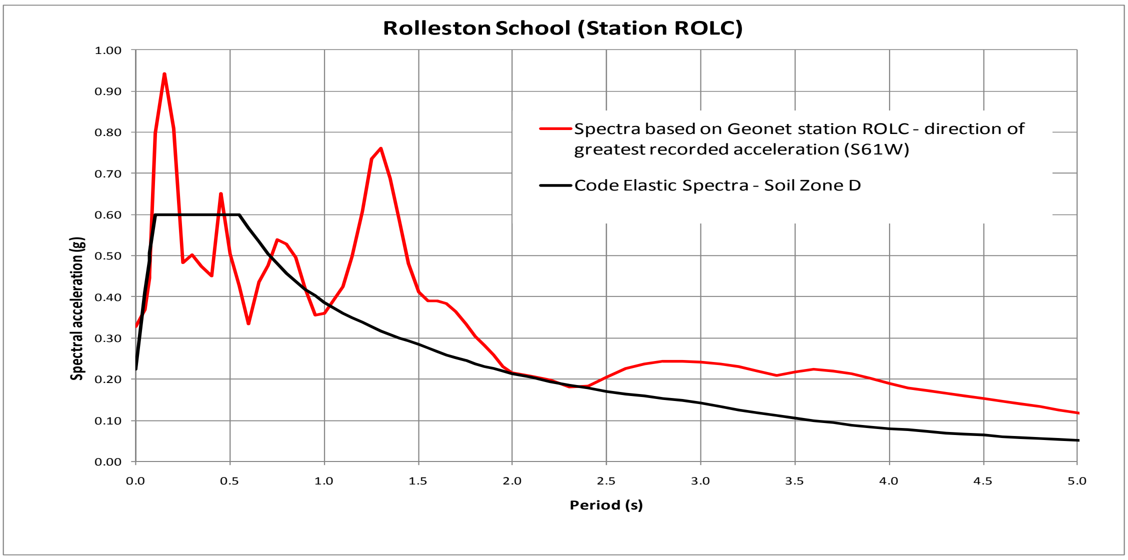

Figure 2 Acceleration response spectra for the S61W direction recorder at Rolleston School

4.2 Incorrect design of the racking members and connections

The principal design standard for racking members is AS/NZS 4600:2005 (SNZ, 2005). The sections used for posts are complicated, and careful determination of the section properties in accordance with this standard is essential, to establish the section capacity and the member capacity. Beam elements are generally closed box sections with less complication. Moment-curvature relationships are required to be established for the beam/post connections and these fed into the system analysis.

The authors have not observed any instances of beam member failures and none have been notified to us. Certainly bent beam members were observed in collapsed racking but it is believed that these were a result of the failure of other elements. In one instance the beams in undamaged racks showed definite signs of deflection under the stock load. In Figure 3, the load on the beams was approximately half of the specified maximum uniformly distributed load.

Figure 3 Beams deflecting under approximately half of the specified maximum UDL

In several known instances, the across-aisle frames had failed. There were a number of failure mechanisms, which could have been the result of incorrect design. Evidence of buckling failure of web members and end connection tension failure of web members was observed. This sometimes led to buckling failure of the posts, the posts having a greater than designed for effective length as a result of the failure of their lateral restraint. Posts were observed that had buckled locally under racking displacement in the down-aisle direction (Figure 4).

Post baseplates failures were also observed. This was sometimes due to failure of the connection between the post and the baseplate (in cases where the baseplate is manufactured with a stub element to which the post is bolted). On other occasions the hold down bolts had torn through the baseplate or otherwise pulled the hold-down bolts from the floor or fractured the bolts.

From the authors observations, it appeared that down-aisle failures were not a primary cause of collapse. There were systems that had a considerable lean in the down-aisle direction after the earthquake but they had not reached a point of collapse. Most of the distortion was due to yielding of the beam/post connections. In terms of the requirements of the First Schedule of the Building Regulations (NZ Government, 1992), the performance in this case has been satisfactory in that the rack has not toppled. However, it would be necessary to dismantle the racking and replace damaged elements to ensure continued safe operation.

4.3 Poor manufacture of rack elements

The authors are aware of some instances where welded connections had failed. When all the energy dissipation down the aisle is expected to take place in the ductile connection between the beam and post, to have a brittle failure in the adjacent welded joint between the beam and the connection bracket (Figure 5) is not acceptable.

4.4 Unapproved alteration of the shelving configuration

It is believed that many racking owners are unaware of the importance of maintaining the designed configuration of the racking system. While the authors have no specific examples of racking failure caused by an unauthorised alteration of the system, such alterations can easily introduce weaknesses that have not been taken into account in the racking system design. Examples include the removal of beams, thus removing the required lateral restraint for the posts.

Figure 4 Down-aisle distortion of post

Figure 5 Failure of welded joint between beam and bracket

4.5 **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 is unable to resist design level earthquake loads.

4.6 **Overloading of the racking by the store owner**

Because the shelf contents are generally much heavier than the self weight of the racking, the seismic demand on the system is very closely related to the weight of the shelf contents. Researcher experience has indicated that in public access storage racking the weight of the shelf contents is lower than the racking is capable of carrying (Berry, 2003). This may well be the reason why public access storage racking appeared to perform well in this earthquake.

Figure 6 An example of a completely filled commercial racking system

On the other hand, commercial racking is generally built to store palletised products over the full height of the system and the beams are installed at levels which just allow full pallets of the stored product to fit. Commercial demands invariably mean that the racking is loaded to very near completely full all of the time (Figure 6).

For bulky items, such a level of "fullness" may not equate to the full loading that the racking is capable of carrying, but for dense products such as cans of produce, the racking will very likely be placing heavy gravity and seismic demands on the racking. In these cases, the designer will hopefully be provided with accurate product weights.

A greater opportunity for the racking to be overloaded occurs, albeit inadvertently, when very dense products are stored. These products may be so dense that if they occupied the full height of an available shelf, the system would be overloaded both under gravity and seismically. It is relatively easy for the shelf levels to be inadvertently overloaded.

Figure 7 Evidence of impact damage to a racking system from the adjacent building structure

4.7 Unrepaired damage caused prior to the earthquake

It is imperative that racking systems are regularly checked for damage that may occur during normal operation and that this damage is repaired as soon as possible after it being discovered. In particular, posts that have been impacted by either loads on forklifts or the forklift forks themselves may still support the gravity loads but the section will have been weakened by the impact and when subjected to the seismic demands, failure will be very likely.

4.8 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. The authors are aware of at least one instance where parts of a rack have impacted the building structure (Figure 7). 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.

5 IMPLICATIONS FOR THE DESIGN GUIDE

The authors do not see any necessity to adjust the content of the Design Guide (Beattie & Deam, 2007) with respect to its application to the design of public access high level storage facilities. However, there are several initiatives that are required if it is to be extended to include commercial 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 commercial systems. 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 are not likely to have the space to slide and this factor may therefore not be relevant for commercial storage systems.

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 storage racking requires a Building Consent. The Department of Building and Housing has advised that the racking system will need to comply with the functional requirements and performance criteria of the New Zealand Building Code (NZBC), as required by Section 17 of the Building Act. Territorial Authorities need to be made aware of this requirement when new storage racking systems are installed within their area of jurisdiction.

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. Some pallet types 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.

6 CONCLUSIONS

An investigation of the performance of the storage racking systems in the Darfield earthquake of 4 September 2010 has shown that high level storage racking in public access stores behaved well with no known collapses. Observations of the performance of commercial racking systems suggested that changes are required to ensure that in the future such systems will not collapse in a design level earthquake. Several possible reasons for the failure of these systems are discussed in this paper. The changes are likely to include increasing the awareness of Territorial Authorities of the need for the racking to be compliant with the NZBC, adjustments to the design loadings for commercial systems and greater highlighting of the need for regular inspection and maintenance of racking.

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