Increasing seismic resilience of pallet racking systems using sliding friction baseplates

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ABSTRACT:

This study proposes a cost-effective method for increasing the resilience of cold-formed steel pallet racks subject to earthquake excitation in the cross-aisle direction. A sliding friction baseplate that dissipates seismic energy effectively has been developed for low and medium-rise pallet racking systems. The seismic performance of a series of low-rise full-scale racking systems having either yielding, rigid or sliding friction baseplates was investigated through snap-back testing where an initial sway was applied to the top of each test frame. The oscillations of the frames and the axial forces incurred in the uprights were recorded and compared between the different types of baseplates. The test results demonstrate that the racking system fitted with the bolt-tightened sliding friction baseplates has significant improvement in the seismic resilience over those fitted with the alternative baseplates, with a larger energy dissipation capacity and a smaller force demand.

1 INTRODUCTION

Cold-formed steel storage racking systems are used extensively worldwide to store goods (C. K. Chen, Scholl, and Blume 1980a). Common types of storage racks include selective racks, drive-in or drive-through racks, cantilever racks and stacker racks. Selective pallet racks are the most commonly used in industrial storage, as shown in Figure 1.

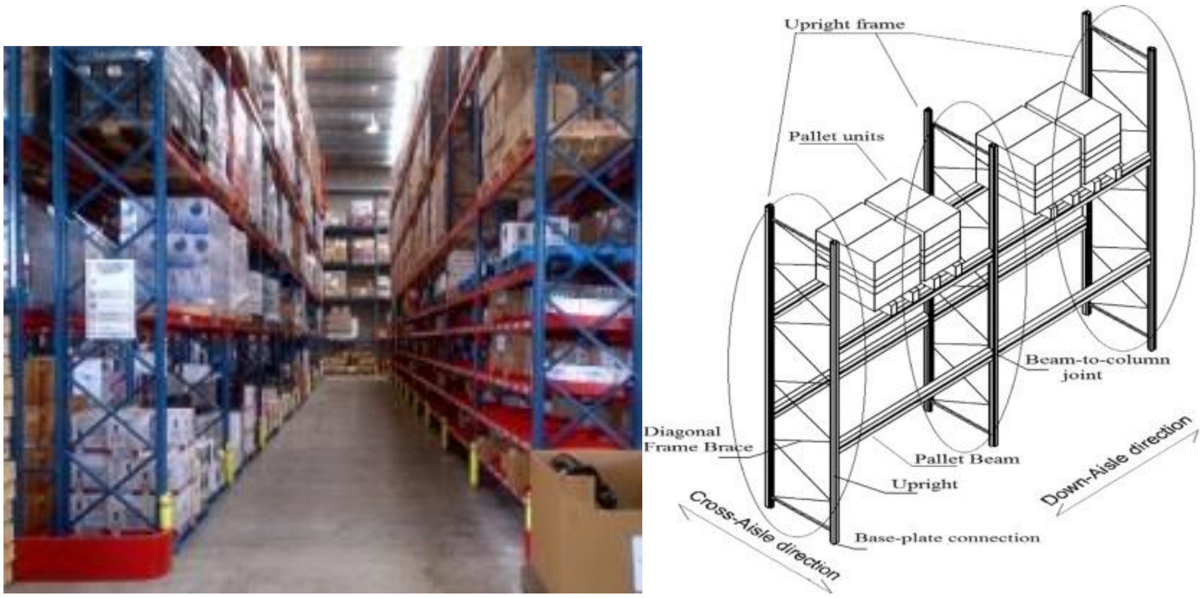


Figure 1. (a): Selective racks; (b): A selective pallet rack frame (adopted from (Bernuzzi and Simoncelli 2016))

The typical selective rack consists of upright frames (laced columns) connected to each other by horizontal beams spanning in the down-aisle direction, as shown in Figure 1b. Uprights have baseplates at the bottom. The baseplates are required by some standards (Australian Standard 2012) to be fixed to the floor with anchorages, but are otherwise unanchored.

The two principal axes for seismic design of pallet racking systems are the cross-aisle direction, which is parallel to the frame bracing system; and the down-aisle direction, which is parallel to the beam span, as shown in Figure 1b. A selective rack is typically considered to be a braced frame in its cross-aisle direction and a moment frame with semi-rigid connections in its down-aisle direction. This paper focuses on the seismic performance of typical selective racks in the cross-aisle direction.

The commonly observed collapse modes of racking systems in the cross-aisle direction during earthquake events are: (**a**) column buckling, as shown in Figure 2 and Figure 3; (**b**) overturning due to insufficient ground anchoring or poor weld quality between the baseplates and the uprights, as shown in Figure ;

Figure 2. Cross-aisle direction failure by column buckling (Connor 2012)

Figure 3. Cross-aisle direction collapse of pallet racking system (ABS Group 2001)

Figure 4. Failure of baseplate to upright connection (Uma and Beattie 2011)

Previous studies have investigated the local and global seismic behaviours of racking systems in the cross-aisle direction by numerical modelling and experimental testing. These researchers found that the energy dissipation capacity and seismic resilience are much weaker in the cross-aisle direction than in the down-aisle direction.

The weak link in the cross-aisle direction is in the upright-base connection (C. K. Chen, Scholl, and Blume 1980b). Even if a robust and well-anchored racking system survives a severe earthquake, the connections will often be either fractured or plastically deformed to the extent of requiring replacement. This outcome means dismantling the rack. Some researchers introduced base isolation techniques to racking systems(Filiatrault et al. 2008; Johnson et al. 2012; Michael et al. 2010). The concept has been verified by a large number of experiments including full-scale shaking table tests and appears to be successful. However, the use of base isolation techniques significantly increases the cost of racking systems. A minimal-damage and low-cost solution to improve the seismic resilience of racking system is desired.

It is interesting to observe that, during the 2010 Darfield Earthquake, in the same warehouse, some un-anchored racks walked off their original position and survived the earthquake with no damage, while the racks that failed were anchored (Crosier, Hannah, and Mukai 2010). This observation is inconsistent with the requirement of most racking standards and design guidelines which require baseplate anchorage for seismic resistance.

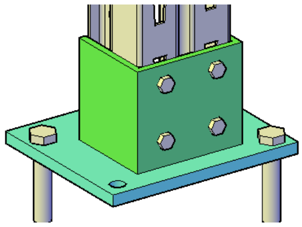
During the 1960 Chilean Earthquake, a number of tall, slender structures survived the strong ground shaking whereas more stable appearing structures were severely damaged (Steinbrugge and Clough 1960). The base of the buildings lifted from its foundation and started the rocking motion. Housner (Housner, George 1963) investigated the rocking behaviour numerically as an inverted pendulum, and found that there is a scale effect that render tall, slender structures more stable against overturning than might have been expected. This finding explains at least in part why the unanchored racks survived the Darfield earthquake.

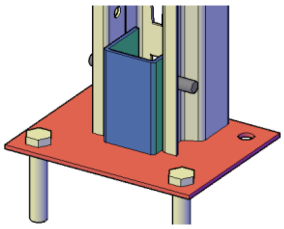
A design concept of controlled rocking structures has since been developed for the pallet racking system, in which the base of the structure or selected upright are permitted to uplift from the foundation in response to severe lateral loading. Dampers were introduced to the system to dissipate energy, with the most frequently used energy dissipation method involving baseplate yielding (Azuhata, Midorikawa, and Ishihara 2005)(Petrone et al. 2016). However, the yielded baseplate will have to be replaced, leading to significant rehabilitation costs. A more robust baseplate that dissipates energy but does not require replacement is desired.

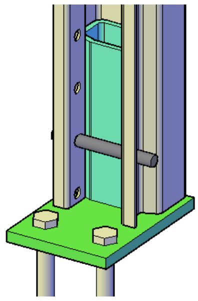
The sliding friction joint developed by Clifton (Clifton 2005) dissipates energy by friction instead of forming a yielding zone in the baseplate. Friction due to sliding between the baseplate and the upright is introduced via a controlled clamping force between the upright and a stub welded to the baseplate. The clamping force is related to the tightening torque of the bolts connecting the baseplate to the upright. Figure 5e illustrates the concept. By adjusting the tightening torque of the bolts, the energy dissipation capacity can be suited to the design needs. This paper describes a series of full-scale snap-back tests that were performed to assess the energy dissipation capacities of the racking systems fitted with the sliding friction baseplate and other types of baseplates.

Figure 5 (a). Frame configuration

(b). The test setup


(c). Rigid baseplate


(d). Yielding baseplate


(e). Friction baseplate

2 THE EXPERIMENT

As shown in Figure 5a, each of the tested rack frames had 3 levels (1.4 m height per level) and 2 bays (1.35 m per bay), and was 0.9 m deep, erected on concrete slabs fixed to the strong floor. Each pallet was 783 kg, clamped to the beams with steel sections and bars. The frame bracing consists of two X-braces at the bottom then K-bracing to the top at 600-mm pitch. The uprights were fitted with four types of baseplates connected to the concrete slabs with anchorage bolts:

I: Rigid baseplate, which does not allow uplift, as shown in Figure 5c.

II: Yielding baseplate, which allows the frame to uplift at the base and dissipate energy through yielding, as shown in Figure 5d.

III: Friction baseplate with a **bolt tightened** to 30 N·m**,** as shown in Figure 5e.

IV: Friction baseplate without bolt tightening**,** which can be considered to be a free-to-rock connection with horizontal shear resistance.

A photograph of the test setup is shown in Figure 5b. A displacement in the cross-aisle direction was applied to the centre of the top level of the rack frame by a hydraulic actuator mounted to a strong wall. A quick-release shackle was used to release the frame that was then allowed to undergo free vibration until the structure came to complete rest.

The column uplift was measured by portal gauges, the longitudinal normal strain at the upright base was recorded with strain gauge sets, and the displacements of the frame at different levels were recorded by wire displacement transducers.

3 OBSERVATIONS AND DISCUSSIONS

3.1 Damage inspection:

Subsequent to the snap-back tests, there was no upright damage observed for the frames fitted with yielding baseplates and friction baseplates (with or without bolt tightening), while a permanent local deformation was observed at one upright fitted with rigid baseplates. Likewise, no significant residual displacement was observed for the former, which tended to self-centre, while a large residual displacement was observed for the latter, as shown in Figure 6.

It is worth noting that the anchor bolts of the rigid baseplates were loosened from the concrete foundation at the application of the horizontal displacement (time zero), although no damage was found in the baseplates themselves.

3.2 General response:

Rocking was observed for the frames fitted with yielding or friction baseplates. The frames rocked in a manner similar to a rigid block, but with the block demonstrating noticeable elastic flexibility. In contrast, the frame fitted with the rigid baseplates underwent significant bending and shearing.

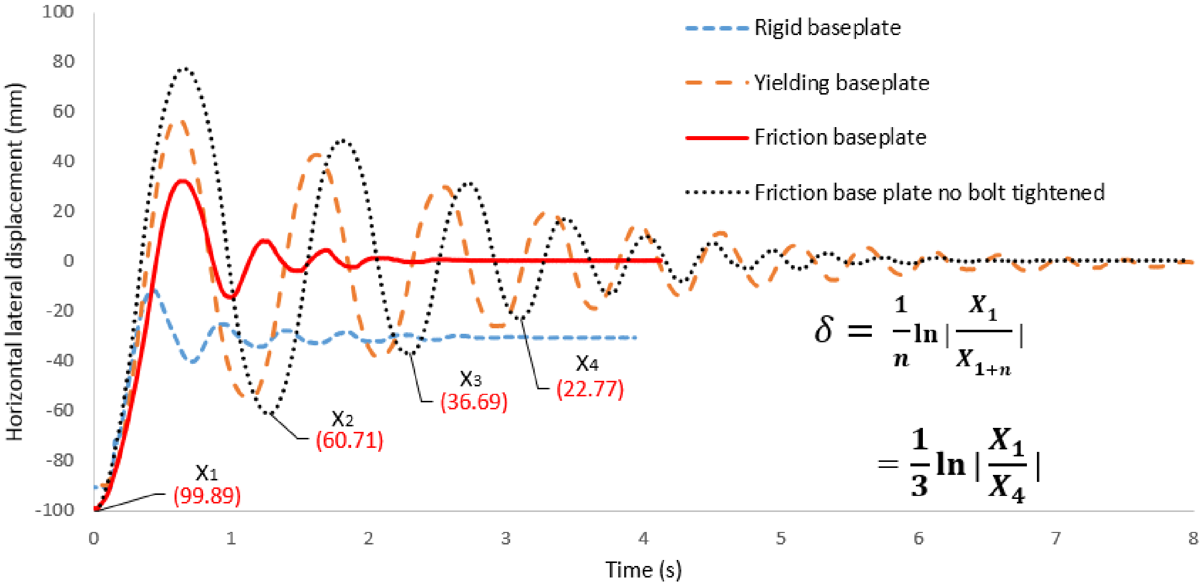


Figure 6. Time-history of horizontal displacements of the middle upright frame with 4 types of baseplate configuration

As can be seen in Figure 6, the frame with bolt-tightened friction baseplates came to rest in about 5 cycles in 2.5 seconds, while that with the yielding baseplates took more than 12 cycles and 8 seconds.

The periods of the first 5 cycles of the free-vibration response of each frame are listed in Table **1**. Only the first 4 cycles can be clearly identified for the bolt-tightened friction baseplate configuration, and the maximum displacement at the 4th cycle was only 1.38 mm without uplift.

The equivalent damping ratios were estimated to give a rough idea of the energy dissipation capacity of various types of baseplates. However, it is important to note that the method of estimating the equivalent damping ratios is based on the viscous damping assumption not friction damping. The logarithmic decrement method was applied, as shown in Figure 6, and the first three cycles are considered for the damping ratio calculation. The damping ratio of the yielding baseplate was found to be 6.6%, which is higher than the values ranging from 0.5% to 3% computed for some conventional baseplates in the cross-aisle direction (C.K. Chen et al. 1980)(Krawinkler et al. 1979). The rigid baseplate had an estimated damping ratio of 16.3%, which is quite high, however, there was a significant residual sway displacement of 30 mm. The bolt-tightened friction baseplate had an estimated damping ratio of 20%, which is the highest of all. Surprisingly, the friction baseplates without tightened bolts had a damping ratio of 7.9%, which is higher than that of the yielding baseplates. It may be caused by the small friction force existing between the upright and the baseplate.

Table 1. Snap-back test results

Base plate configuration	**Period of cycles (s)**					**Equivalent damping ratio (calculated from the first 3 cycles)**
Cycle number:	**1**	**2**	**3**	**4**	**5**	
Rigid baseplate	0.61	0.47	0.45	0.40	0.37	16.3%
Yielding baseplate:	1.04	0.94	0.87	0.70	0.63	6.6%
Friction base plate with no bolt tightened	1.30	1.00	0.82	0.65	0.53	7.9%
Friction base plate with bolt tightened	0.97	0.47	0.39	0.42	N/A	20.0%

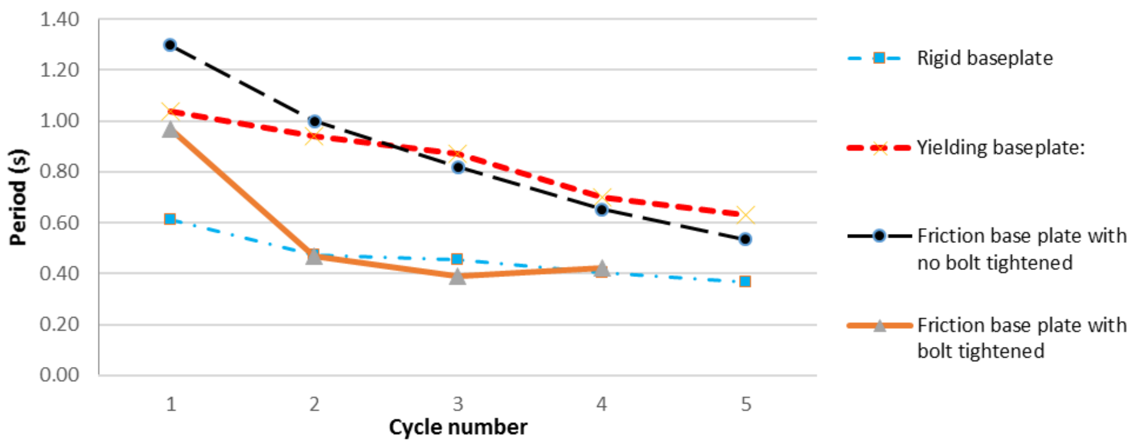


Figure 7. Oscillation periods of test frames

Figure 7 shows that, in general, the oscillation periods of each frame subjected to the snap-back test decreased from one cycle to the next. However, it may be noted that the oscillation period of the frame fitted with the sliding friction baseplate increased between the third and the fourth cycle. The exact reason is unknown to the authors at this stage.

Figure 8 illustrates the uplift time-history at both upright bases of the middle upright frame for all baseplates allowed to uplift, and the strain-uplift curves. The red line in the figure is the uplift measured at the front leg of the frame, the green line is the uplift measured at the back leg of the frame. The uplift of associated with the bolt-tightened friction baseplates decayed much faster than that of the other two uplifting baseplates. The second uplift was only slightly more than a quarter of the first. This excellent performance indicates that the energy input was rapidly dissipated by the friction baseplates in the first half cycle, which is advantageous for increasing the seismic resilience of pallet racking systems.

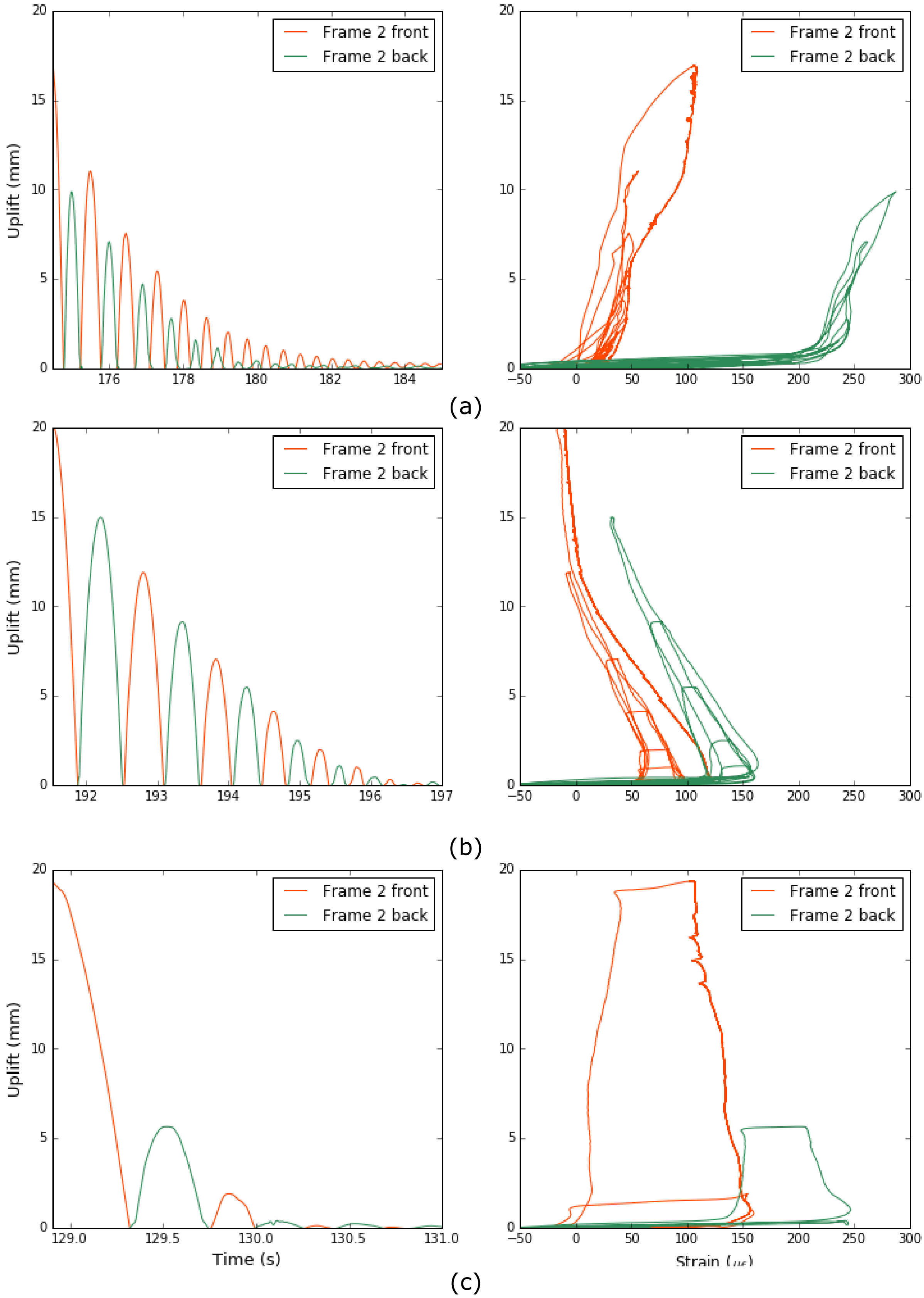


Figure 8. Uplift time-history at upright base (left) and strain-uplift curves (right) of (a) Yielding baseplate; (b) Friction baseplate without tightened bolt; (c) Friction baseplate with tightened bolt.

Since the strain readings were linearly proportional to the upright force, the area enveloped in each loop illustrates the amount of energy dissipated by either yielding (Fig. 8a) or friction (Figs 8b, c) in each cycle of rocking. It is can be seen that the amount of energy dissipated by the bolt-tightened friction baseplate is much higher than that by the other two uplifting baseplates. Also, it is important to note that, while the tightened friction baseplates dissipated much more energy during rocking, its deformation or force demand was the lowest.

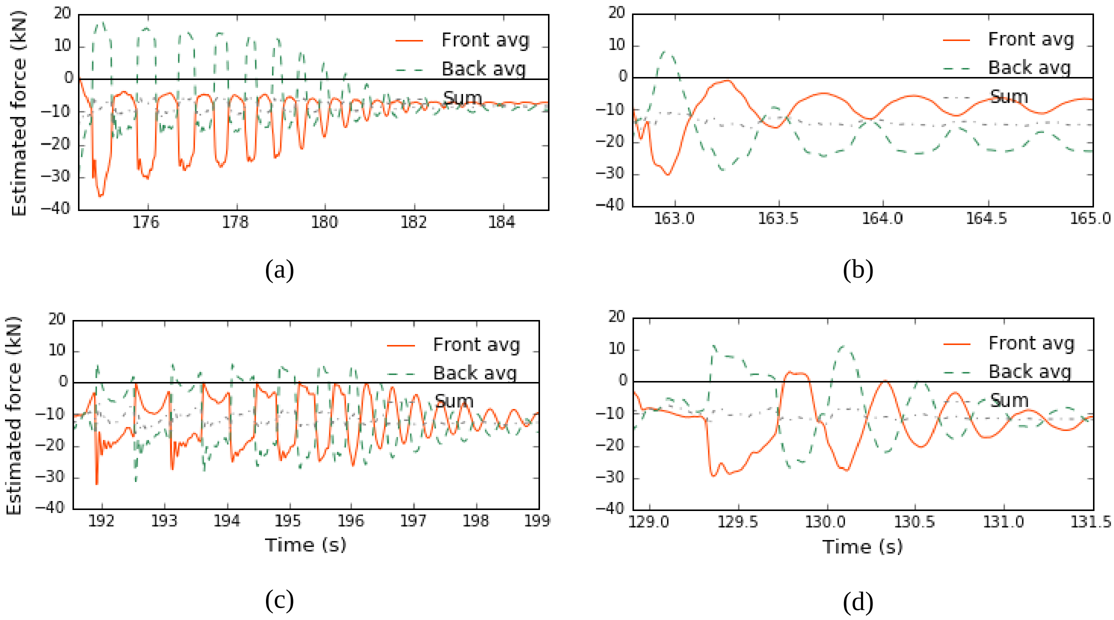


Figure 9. Column force, positive is tension, negative is compression. (a) Yielding baseplate; (b) Rigid baseplate; (c) Friction baseplate without tightened bolt; (d) Friction baseplate with bolt tightened

Figure 9 plots the axial force in the upright adjacent to the base over time, measured by the strain gauges. It can be seen that either for compression or tension, the uprights with friction baseplates had smaller force demand compared to the yielding baseplates. For the rigid baseplates, since the anchor bolt was loosened during the application of the initial sway, the amount of tension force was not significant. However, the maximum compression force was slightly larger than that of the friction baseplates.

4 CONCLUSIONS

A cost-effective method for improving the seismic resilience of cold-formed steel pallet racks has been proposed in this paper, in the form of a sliding friction baseplate. Through snap-back testing, the seismic performance of the sliding friction baseplate was compared to that of yielding and rigid baseplates commonly used in the storage racking industry. It was found that the bolt-tightened sliding friction baseplate resulted in greater seismic resilience due to its larger energy dissipation capacity and smaller force demand.

This study mainly focuses on the seismic design of standard selective pallet racks. However, the design concept described in this study has a real potential to be applied to all types of racks and even other types of light steel framed structures, i.e., scaffoldings or cold formed steel framed houses.

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