
Pinching-Free Connector (PFC): Development and Application in Rocking Timber Walls and Steel Braced Frames

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ABSTRACT

Recent studies indicate that ratcheting mechanisms may provide the ideal structural behavior for resisting earthquakes. One-way ratchets resist only the destabilizing loads that push structures off-center. In reverse, ratchets disengage so that structures are gently encouraged back to the upright, central position. By maximizing damping without residual deformations, such behavior achieves the optimal balance between seismic performance and post-earthquake serviceability.

The Pinching-Free Connector (PFC) is one such ratcheting connector made from standard screw threads. It was developed to mitigate pinched hysteresis loops, where ratchets are used to counteract cumulative damage in traditionally susceptible systems. Working equations derived for the PFC were validated through a non-destructive test protocol conceived for ratchets.

In the first application, PFCs were applied as hold-downs for a rocking cross-laminated timber wall. Pseudo-dynamic tests showed that PFCs eliminated pinching in the wall system, enabling large dissipation with full hysteresis loops. PFCs near the rocking toe generated additional restoring forces between 0.6–2% drift, helping prevent perceptible levels of residual deformations ($\geq 0.5\%$).

In a second application, the PFC was used to mitigate pinching in tension-only braces for steel frames. A ratchet stopper was incorporated to control the ratcheting during fully-reversed cycles. Again, large dissipation and small restoring forces were possible with a small spring sufficient to re-center the frame. A numerical procedure could predict the frame's cyclic response based only on PFC monotonic test data. These applications highlight the versatility and efficiency of ratcheting mechanisms which do not require buckling restraints nor post-tensioning for optimal behavior.

1 INTRODUCTION

Pinching commonly refers to a reduced load-bearing capacity which impairs stiffness of structures (Ibarra et al. 2005). It is characterised by a pinched shape in the load-deformation graph, as shown by the hysteresis plots in Figure 1. When pinching appears, it usually indicates that the joint or system has been irreversibly damaged by a prior/large loading cycle, impairing the performance in subsequent cycles. Pinching arises:

1. In timber structures, nails or bolts are often designed to crush the surrounding wood fibres irreversibly to ensure a ductile response to earthquake loads. However, by creating wiggle room around the fastener, it results in a degree of slackness or loss of stiffness (Gavric et al. 2015).
2. In steel structures, slender steel braces may elongate permanently under tensile yielding, and subsequently buckle under compression (Tremblay et al. 2003). This generates slackness which can only grow further.

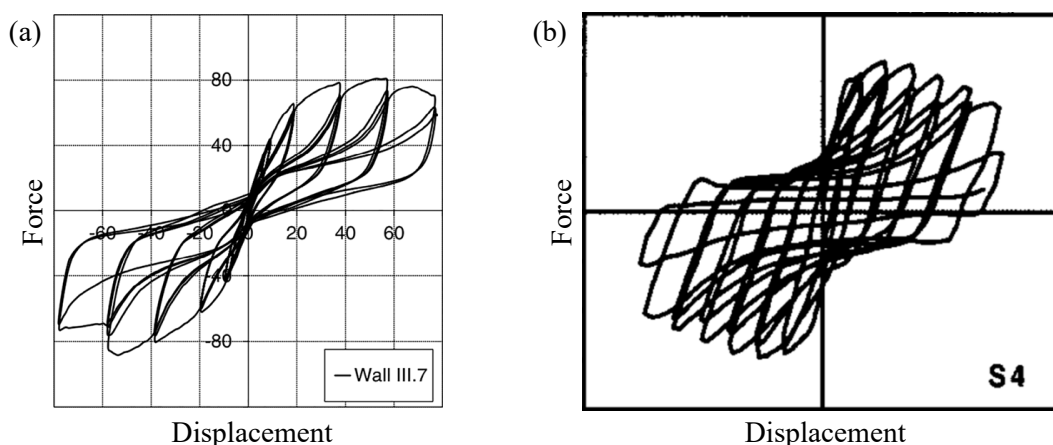


Figure 1: Pinched hysteresis in (a) timber walls, (b) steel frames (Gavric et al. 2015; Tremblay et al. 2003).

Pinching tends to result in larger peak deformations due to the loss of stiffness and dissipative capability (Gusella et al. 2019; Ibarra et al. 2005; Medina and Krawinkler 2004). Pinched systems are also more vulnerable to aftershocks due to the cumulative damage (Aloisio et al. 2022; Pu and Wu 2018). These findings are relevant to Christchurch post-2011 given the shift towards tighter drift limits to mitigate structural and non-structural damage (Bruneau and MacRae 2017; Dhakal 2024; Marquis et al. 2017). Notably, design codes discourage pinching indirectly by imposing restrictions on fastener diameter (for timber structures) or slenderness limits on braces (for steel structures) if not outright prohibiting them (AISC 2016; CEN (Comité Européen de Normalisation) 2004a; b; Mehrabi et al. 2019).

More holistically, seismic resilience critically depends on a balanced amount of hysteretic damping (Jafari et al. 2025; Moussa et al. 2025). This is because post-earthquake serviceability deteriorates at high damping (as it causes residual deformations) as well as low damping (as it leads to damaging displacements/accelerations) even if the structure self-centers. The sensitivity to damping leads to narrow limits on acceptable levels of damping (Jafari et al. 2025) and further emphasizes the necessity for small and sufficient restoring forces.

To achieve this optimal balance between seismic performance and post-earthquake serviceability, ratcheting connectors are a potential solution for providing such ‘checkerboard’ hysteresis shapes (Bai et al. 2025; Chan et al. 2021, 2023b; a; Cook et al. 2018; Dal Lago et al. 2021). Ratcheting connectors normally resist the destabilizing loads only, damping the vibrations in the process of swaying/rocking. They do not impose restoring forces of their own; neither do they resist re-centering motions. Re-centering occurs gently, unaided and unhindered (Eatherton and Hajar 2011; Macrae and Kawashima 1997). This behaviour leads to an ideal hysteresis desired not just for resisting earthquakes, but also for restoring functionality post-earthquake.

2 METHODOLOGY

2.1 PFC Design and Testing

The PFC was developed at the University of Auckland to mitigate pinching in various structural systems. It builds upon prior and ongoing work at the University of Canterbury (Cook et al. 2018; Rangwani et al. 2023).

To describe it simply, the PFC works as a one-way ratchet that ‘locks up’ in tension when a destabilizing force acts on the structure. During strong shaking, a steel rod attached to the ratchet may yield under tension to dissipate seismic energy (Figure 2).

In compression, the ratchet disengages, unloads and re-centers without impediment. Yet, it may readily re-engage at any moment under tension from destabilizing forces (Figure 3).

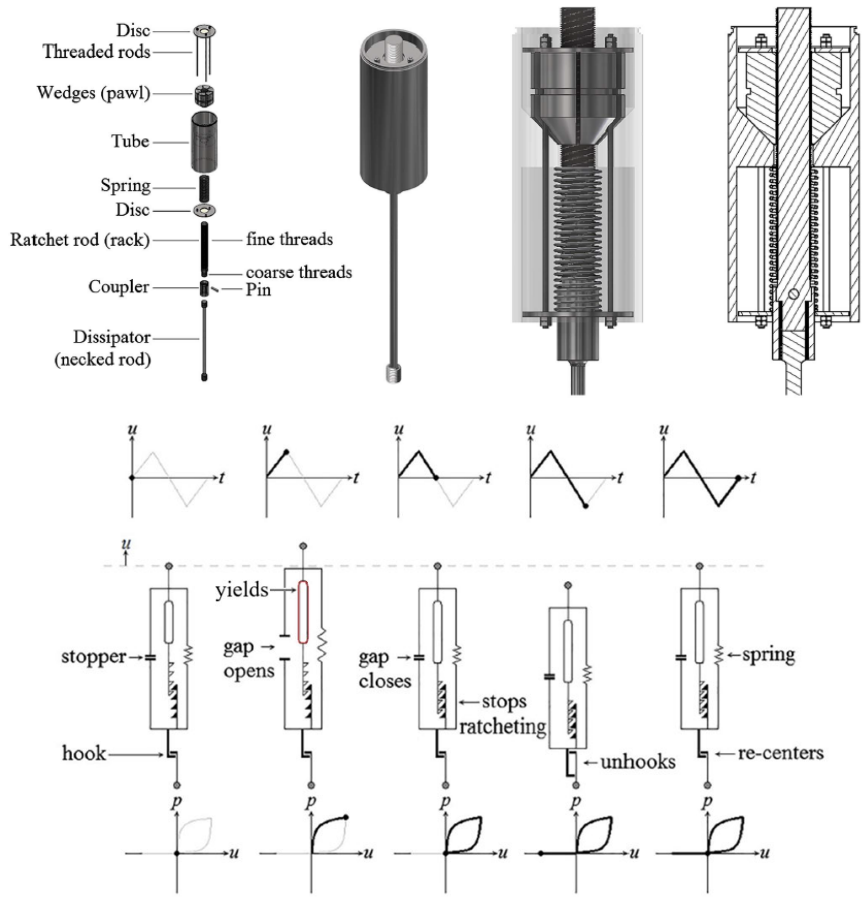


Figure 2: Schematic of ratcheting damper (Chan et al. 2023b).

The effective pitch of the ratchet p_{eff} is related to the distance from one ‘tooth’ to the next. If this distance is too large, then the backlash in the ratchet may be correspondingly large. This is not desirable because then there is a degree of looseness (or slackness) before the teeth interlock again to resist loads. Hence, it is necessary to quantify the effective pitch as shown in Equation 1 for screw threads (Chan et al. 2023b).

$$p_{eff} \approx p + \frac{p}{2\pi} \left(\frac{\theta_{AB}}{2} - \eta \right) - 0.65p \tan(\alpha) + \left[\frac{\cos(\eta)}{2} - \frac{\sin(\eta)}{\tan\left(\frac{\theta_{AB}}{2}\right)} \right] d_n \tan(\beta) \quad (1)$$

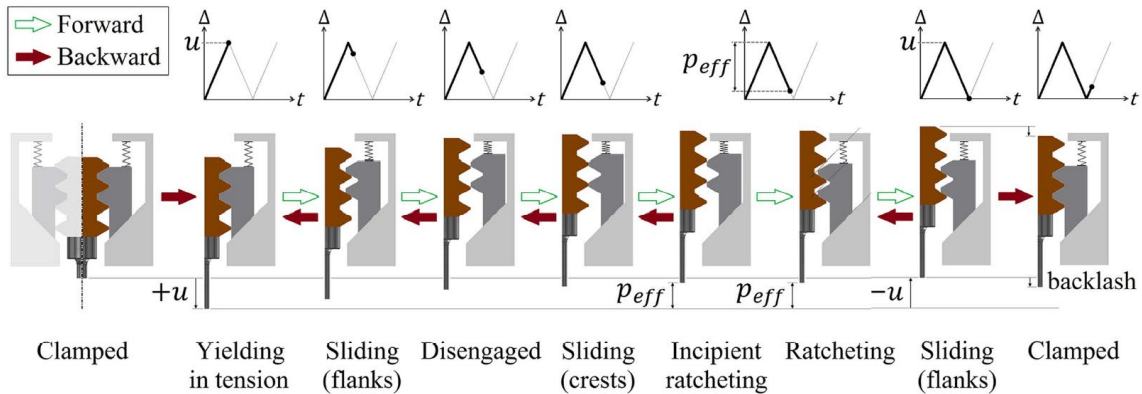


Figure 3: Illustrating the ratcheting mechanism of the PFC (Chan et al. 2023b).

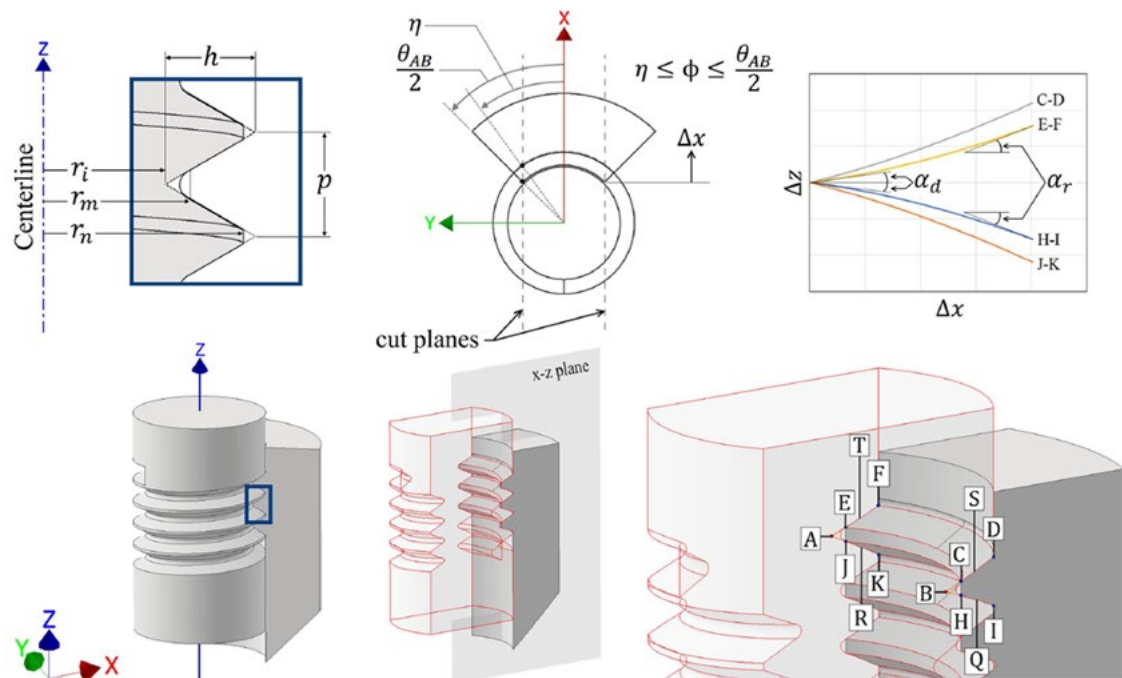


Figure 4: Teeth of the ratchet made from metric screw threads.

... where η is a reduced circular angle (Figure 4) calculated as $\eta = \sin^{-1} \left[\left(1 - 1.3 \frac{p}{d_n} \right) \sin \left(\frac{\theta_{AB}}{2} \right) \right]$. The variables α is the angle of thread flanks, β is the angle of collet taper from the horizontal, θ_{AB} is the circular angle of each split collet, p is the pitch of the threads, and d_n is the nominal diameter of the threads.

Equilibrium conditions need to be satisfied also to ensure smooth operation of the ratchet. These result in design constraints (e.g., geometric) which are not listed here due to space limitations. However, they are necessary for the ratcheting mechanism to engage/disengage without jamming; detailed equations and their derivation are available along with accompanying supplementary materials (Chan et al. 2023b). To verify the design limits, several geometric parameters were tested through non-destructive ratcheting tests (Table 1).

Figure 5 shows the mixed loading protocol used for non-destructive ratcheting tests. It combines displacement-control in compression and force-control in tension. This is because compression strokes trigger ratcheting in the device, after which reverse loading puts the device in tension almost immediately. The tensile load limit was set at $P = 1$ kN to avoid yielding the rod for repeat testing. It also allows the mechanism to start and end each cycle in a 'clamped' state to obtain the effective pitch. In compression, the displacement target was set to increase by 1 mm on every cycle. A constant speed of 20 mm/min was applied in these tests.

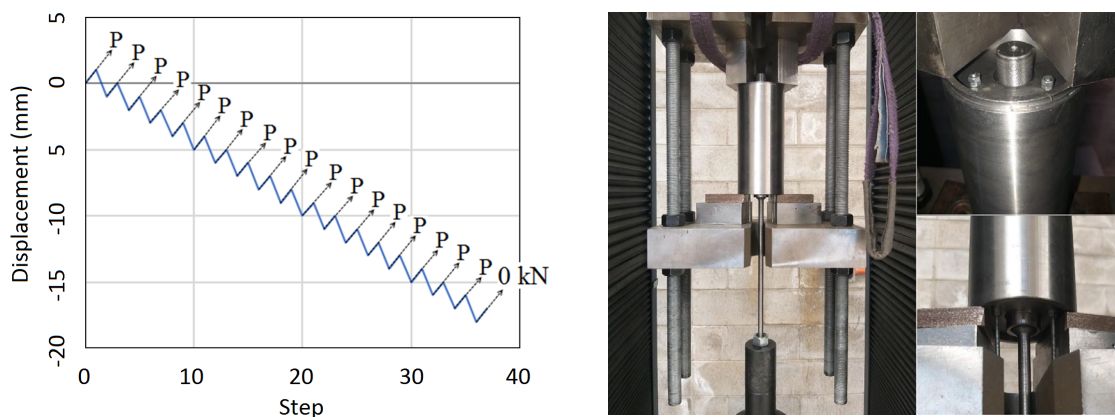


Figure 5: Mixed load protocol for ratcheting tests.

Table 1. List of configurations for ratcheting tests and the parameters varied.

Test	Size	Pitch (mm)	Threads/inch	Num. collets	Circ. angle	Taper angle
A1	M24	2	12.7	3	96°	45°
A2	M24	2	12.7	6	38°	45°
B1	M24	2	12.7	3	96°	60°
B2	M24	2	12.7	6	38°	60°
C	M24	1	25.4	6	55°	45°
D	M24	0.5	50.8	6	55°	45°

2.2 Application in Rocking Timber Wall

PFCs were used to hold down a rocking cross-laminated timber (CLT) wall made of 3×42 mm layers and $1200 \times 3000 \times 126$ mm in size (Figure 6). It was loaded laterally by an actuator with swivel joints. A support frame provided out-of-plane restraints. At the bottom corners, shear key brackets resist in-plane shear (and induce rocking) as well as out-of-plane movement. Base plates were 36 mm thick, each plate fastened to the strong floor by 4×27 mm diameter rods at 500 mm grid spacing and post-tensioned to 100 kN.

Actuator loads were transferred to the wall panel through a pair of steel channels at 2315 mm height. The channels were fastened rigidly onto the wall using $6 \times M20$ bolts. The loading speed was 144 mm/s in the pseudo-dynamic test. Prior to this, the bare response of the wall system was obtained first by running tests without any hold-downs attached to the wall.

The load protocol consisted of 2 cycles at drift increments of 0.5%. Given the limited elongation capacities of PFC rods, it was decided that more insight into the wall behavior could be gained from fewer cycles at each amplitude. This meant that a higher level of drift could be attained prior to rupture. This information was deemed to be more valuable than additional cycles of ratcheting/hardening at low amplitudes. Lateral movement of the wall was measured using a string potentiometer at the same height as the actuator. Linear potentiometers were used to record PFC deformations as well as the uplift at each end of the wall.

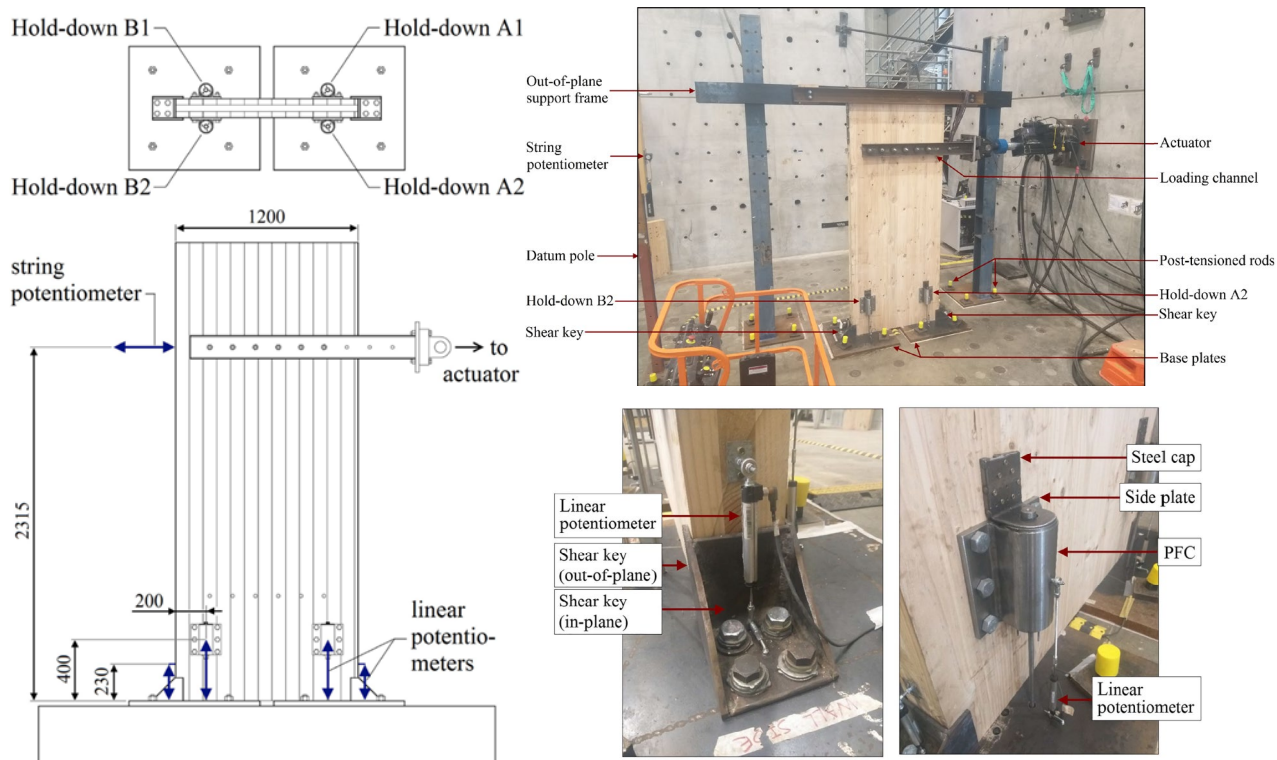


Figure 6: Rocking cross-laminated timber (CLT) wall with PFC hold-downs and shear keys at the corners.

2.3 Application in Steel Braced Frame

A preliminary test was performed also for a potential application in braced frames (Figure 7). As tension-only braces, this version of PFC contained additional ratchet stopper to cease ratcheting at the plumb position.

The frame was set-up on the floor using steel brackets to transfer horizontal reactions at the top and bottom of the frame. The beam and columns were 75 x 75 x 4 mm hollow square sections with pinned connections. M30 threaded rods were used as the brace, which was also pinned on both ends. As the maximum length of rod available was 1 m, a coupler was used to join two pieces of M30 rods together. Ball bearings were placed under scrap pieces of plywood to support the weight of the frame. This ensured that the friction against the floor did not affect the response significantly. Only one brace was built and tested in this study to trial the self-centering concept.

A hydraulic jack was used to apply the loads through three steel brackets bolted along the beam. The loading protocol consisted of five fully reversed cycles at amplitudes from 10 mm to 50 mm, in 10 mm increments. This translates to a peak drift of approximately 2%. Only one cycle was performed at each amplitude to illustrate more clearly the ratcheting and hardening behavior.

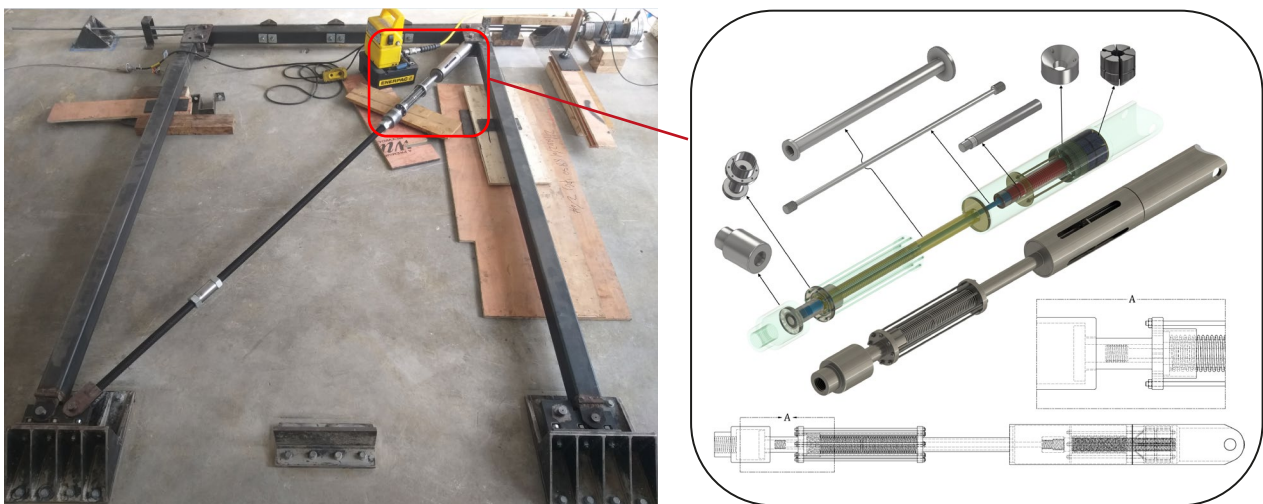


Figure 7: Steel braced frame.

3 RESULTS

3.1 Non-Destructive Ratcheting Tests

The results of the non-destructive ratcheting tests are shown in Figure 8 and summarized in Table 2. On average, the effective pitch was found to match the predicted values very well.

Table 2. Summary of ratcheting test results.

Test	p (mm)	Effective pitch, p_{eff} (mm)	Average p_{eff}	Predict p_{eff}
A1	2.0	Ratcheting not possible due to low thread flank angle	-	-
A2	2.0	2.476, 2.450, 2.487, 2.462, 2.456, 2.441, 2.434, 2.454, 2.451	2.46	2.44
B1	2.0	Ratcheting not possible due to low thread flank angle	-	-
B2	2.0	3.122, 3.097, 3.096, 3.122, 3.113, 3.116, 3.128, 3.105, 3.099	3.11	3.13
C	1.0	1.394, 1.346, 1.354, 1.375, 1.382, 1.370, 1.376, 1.367, 1.386, 1.391, 1.381, 1.376, 1.372, 1.379, 1.379, 1.389, 1.356, 1.378, 1.365	1.37	1.38
D	0.5	0.644, 0.702, 0.732, 0.666, 0.689, 0.702, 0.670, 0.703, 0.753, 0.682, 0.718, 0.740, 0.687, 0.696, 0.691, 0.658, 0.689, 0.712, 0.675, 0.704	0.70	0.69

In tension, load spikes coincide with displacement peaks, indicating that the collets are properly clamped and ratchet is fully engaged to resist loads.

In compression, the load is approximately 0.5 kN which is the force exerted by the compression spring acting constantly on the collets. This ensures that the collets ratchet onto the next set of teeth whenever the opportunity arises.

As expected, no ratcheting occurred in Tests A1 and B1 due to low sliding angle at the teeth.

Smaller spikes in compression can be seen at instances when collets audibly ratchet onto the next set of teeth. The reason for sudden and temporarily reduced compression is because collets have totally disengaged from the threads of the rod. Now resting on the conical taper, reaction forces of the spring pass through the PFC housing (i.e., self-reacting) rather than through the threads/teeth of the ratchet rod.

When ratcheting is possible, it can be seen that the test ends in a shorter time for smaller pitch sizes. This is because smaller effective pitch leads to smaller backlash. Hence, it takes less time for the ratchet to re-engage under force-controlled tension.

These tests show that ratcheting can occur reliably even with the collets being split into 6 pieces.

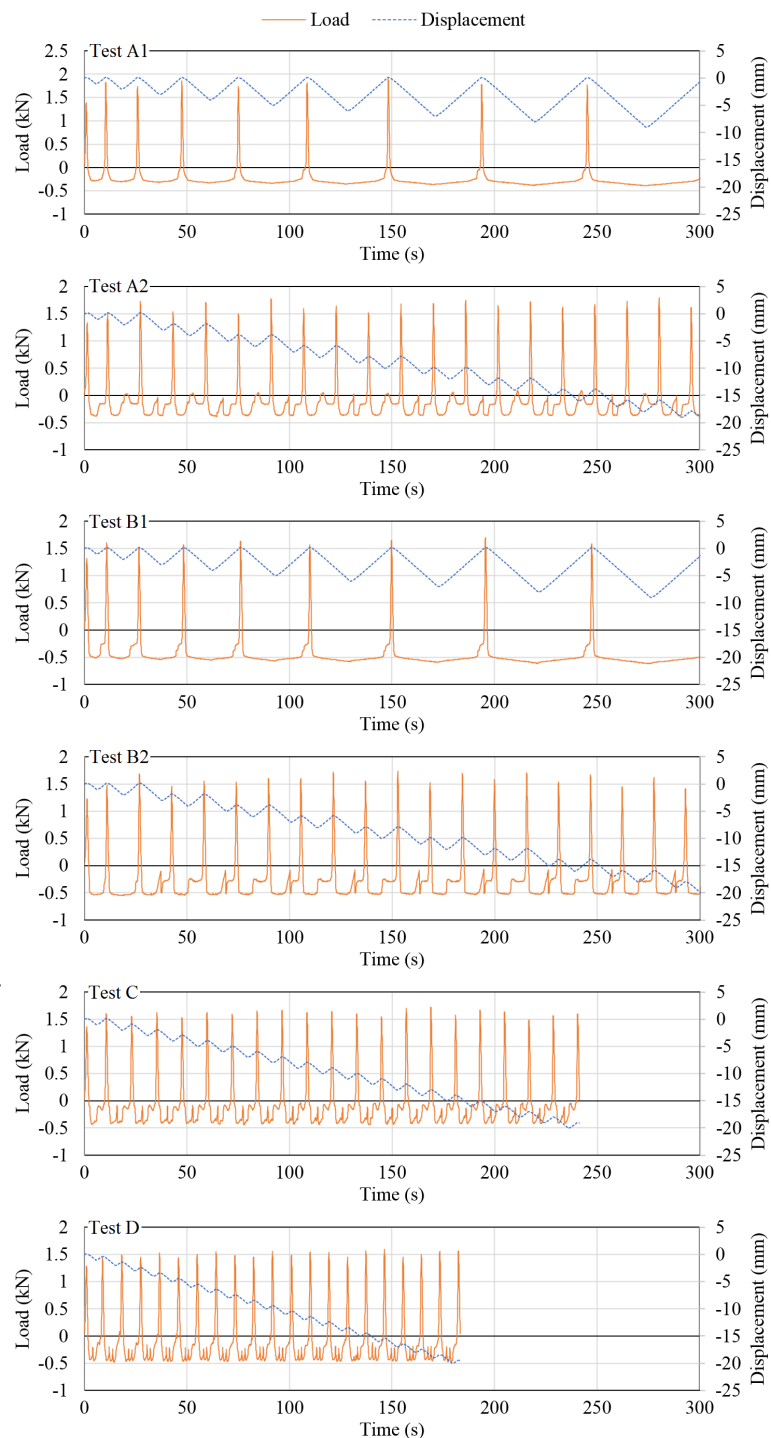


Figure 8: Time history response from ratcheting tests.

3.2 Ratcheting Test with Dissipator

PFC ratcheting test was also performed with a yielding rod to ensure that no jamming occurs at the operating load, and that the collets can engage and disengage successfully during load-unload cycles. This is important because initial prototypes have experienced jamming due to unsuitable taper angles typically used for post-tension anchors. For the ratcheting test in Figure 9, a disposable rod was used (Grade 8.8) mainly to verify that ratcheting was possible at elevated loads. A slack of 1.30 mm was observed and it falls within the maximum possible value of 1.38 mm determined by the effective pitch (from Equation 1). There was no visible damage to the threads.

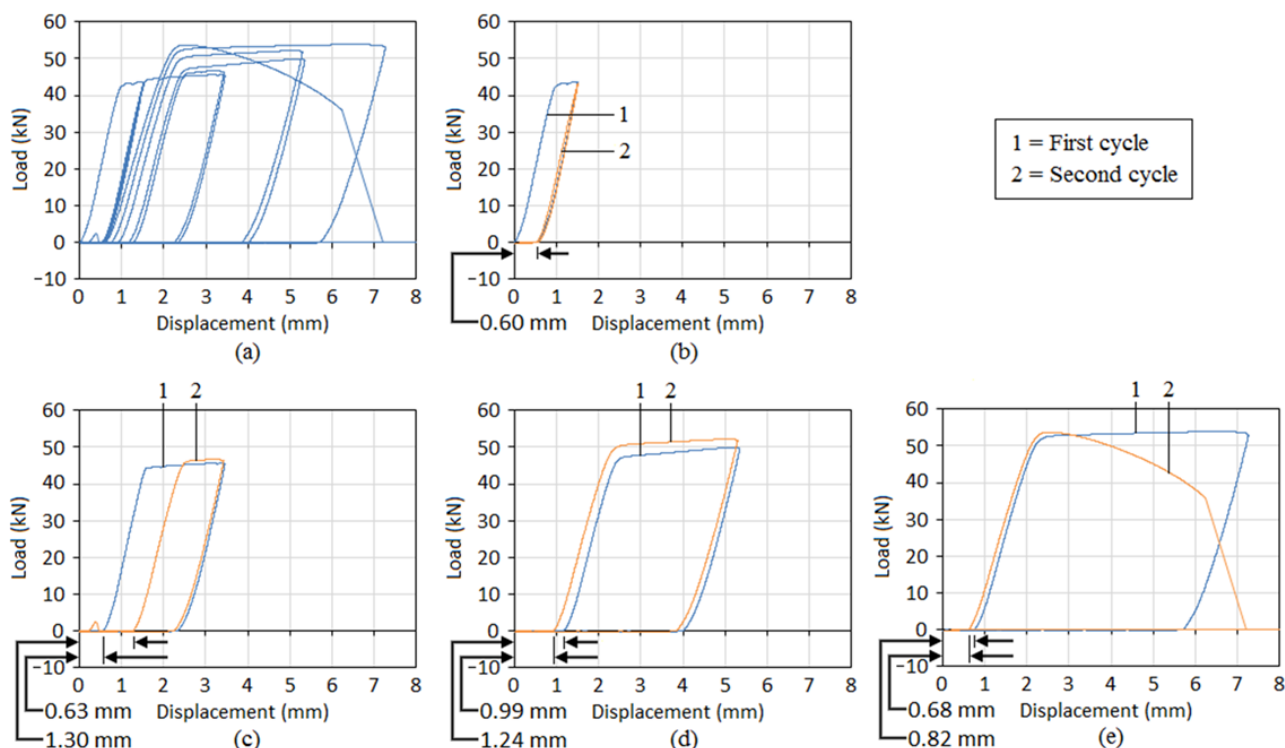


Figure 9: Cyclic test of the PFC performed with Grade 8.8 steel rods.

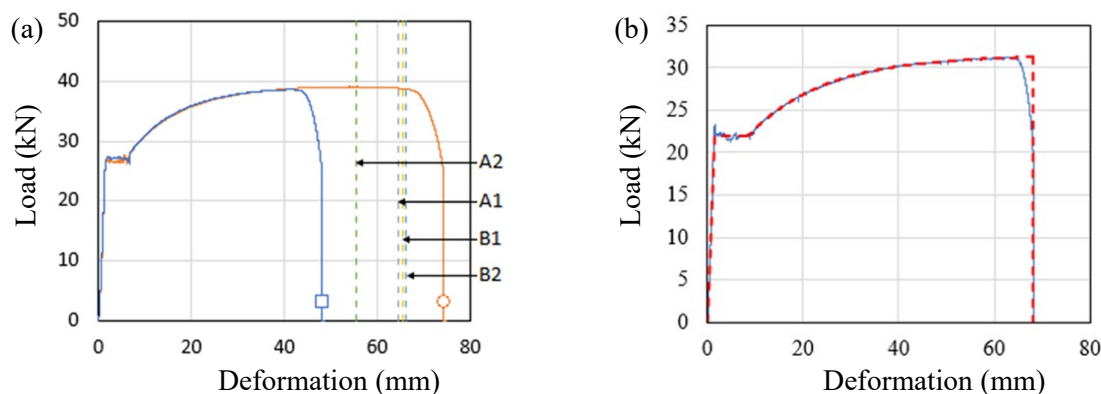


Figure 10: Monotonic tests of the PFC used for (a) rocking wall, (b) braced frame. Grade 300E steel rods.

More ductile rods were subsequently used in actual tests of the rocking wall and the braced frame. They were machined from reinforcing bars meant for seismic applications (Grade 300E). Figure 10 shows the monotonic test results for these rod samples. It is noted that the information required to model ratcheting systems can be obtained more conveniently from monotonic (not cyclic) test data of the dissipator. The yielding element can then be modelled in series with a separate ratcheting element in numerical models.

3.3 Rocking Wall Response

No pinching occurred in the wall system, showing full hysteresis loops instead in Figure 11(b). Additionally, restoring forces were generated at 0.6–2.0% drift. This finding is important because residual drifts start to become noticeable at 0.5% (McCormick et al. 2008). The source of the restoring forces was the elastic response of PFC hold-downs near the rocking toe. This is shown in Figure 11(c). Gravity did not contribute to the positive slope of restoring forces, as Figure 11(a) shows it was rather constant up to 2%. Hence, the wall system is capable of re-centering even though the ratchet was not explicitly designed with this in mind.

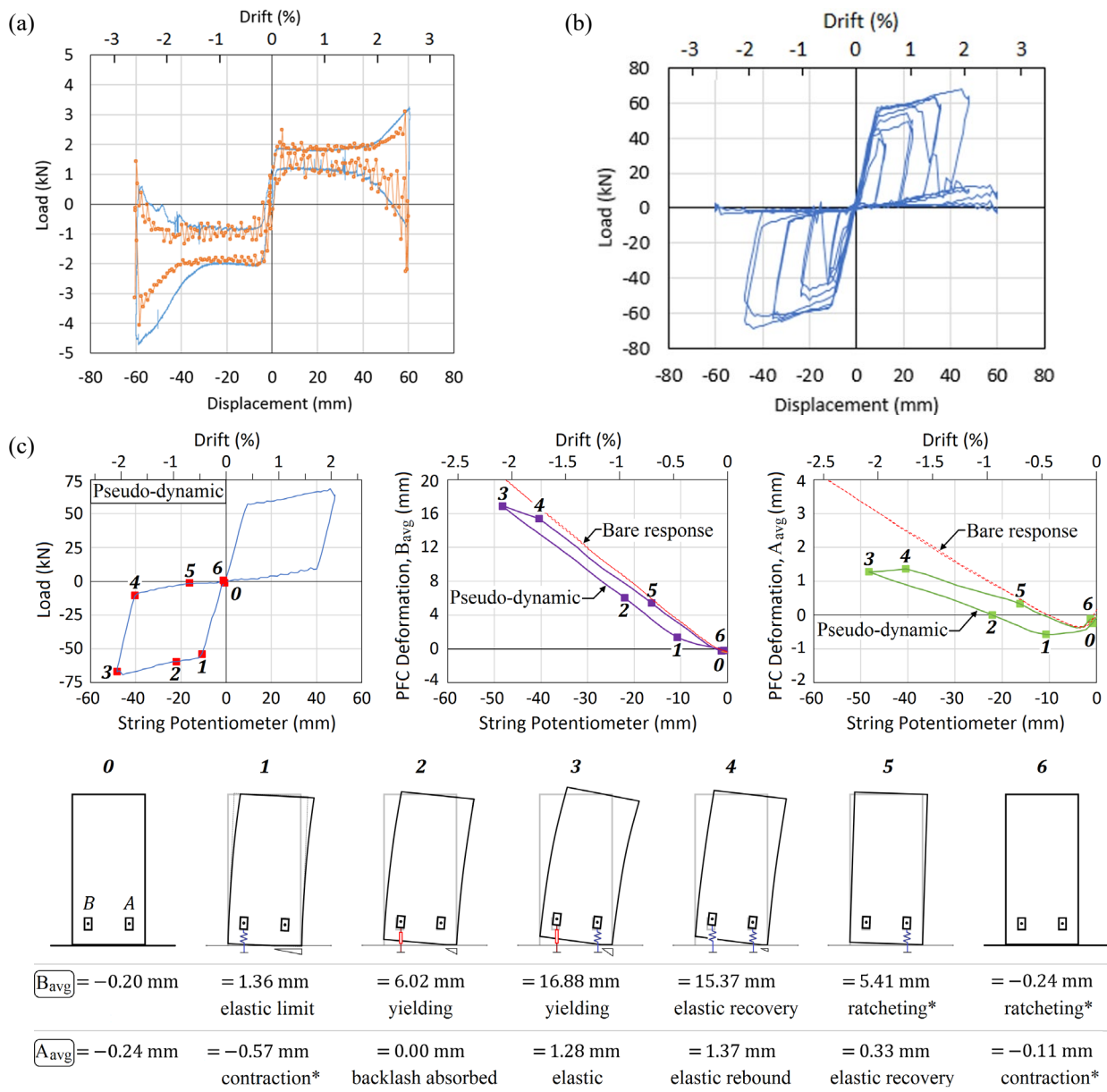


Figure 11: Rocking wall response. (a) no hold-downs, (b) with PFC hold-downs, (c) PFC local responses.

This experiment demonstrated excellent performance of the rocking toe even without the use of protective steel caps. Absence of toe damage may be because PFC hold-downs reduce compression forces on the toe by 40% for the same lateral resistance as post-tensioned systems (Chan et al. 2023a) if PT contribution of 60% is assumed (Granello et al. 2020). This is simply due to a bigger lever arm of the dissipator compared to PT bars. Reduced stresses on the toe is beneficial since crushing/splitting of the toe leads to strength degradation even if PT bars do not yield (Ganey et al. 2017). By maintaining the integrity of the rocking toe, the initial stiffness is preserved, pinching is prevented, and additional restoring forces become possible.

3.4 Braced Frame Response

Pinching was significantly mitigated in the braced frame. Backlash in the ratchet led to minor but visible slack, although they remain below typical limits for serviceability requirements. An excellent match was obtained between test results and numerical model. The computed backlash did not always coincide with the test data, being slightly greater or smaller on some cycles. However, as the test progressed, an overall match in lateral resistance shows that the cumulative amount of ratcheting was consistent with the test results.

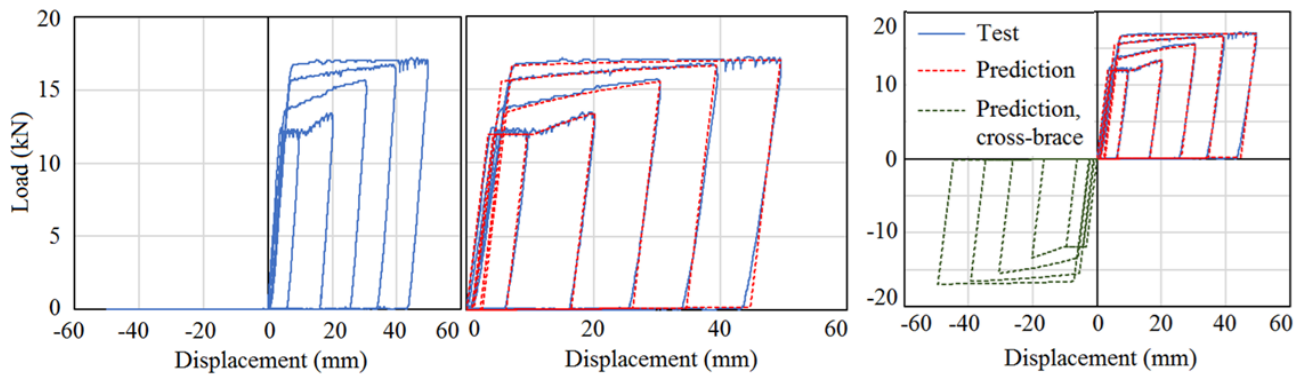


Figure 12: Response of the steel braced frame.

The frame tested involved only one diagonal brace instead of a pair of cross-braces. However, in a cross-brace configuration, it is anticipated that the response would be symmetric because each brace unhooks immediately when crossing over the center position and therefore works in their respective directions only.

These application tests leave room for further improvement in terms of the cumulative ductility. This is because studies have found that cumulative deformation per event can range between 3–10 times the largest cycle, notwithstanding aftershocks (Chan et al. 2021; Cook et al. 2019). Longer steel rods are possible but increasing the length leads to smaller axial stiffness, potentially affecting serviceability requirements. Stainless steel rods are more ductile although more costly, and they exhibit substantial hardening (overstrength). Friction dissipators are another alternative that are currently being researched (Bai et al. 2025; Rangwani et al. 2023).

4 CONCLUSIONS

Ratcheting devices are known for their balanced damping and self-centering capabilities. This desirable combination leads to an ideal structural response, providing the optimal solution when both seismic performance (during earthquakes) and post-earthquake serviceability are considered simultaneously.

The PFC is one such ratcheting connector developed to mitigate pinching in hysteresis loops (i.e., a loss of stiffness). As a ratchet, it resists destabilizing forces only, while gently encouraging structures to re-center back to an upright, central position. The main findings of the studies conducted are as follows:

1. A functioning ratchet was created successfully with fine screw threads (e.g., 0.5 mm pitch). Derived equations were in excellent agreement with the effective pitch and the sliding conditions necessary for ratcheting. These design limits were tested and verified through non-destructive ratcheting tests.
2. When PFCs were used to hold down a rocking timber wall, pinching was virtually eliminated, producing full hysteresis loops. Although unintended, PFCs at rocking toes appeared to generate additional restoring forces over higher levels of drift (0.6–2%). This provides an extra assurance against perceptible levels of residual deformation ($\geq 0.5\%$). There was no visible damage to the toe.
3. When PFCs were used to brace a steel frame concentrically, pinching was mitigated significantly and hysteretic dissipation was maximized. Small backlash was visible due to a larger thread pitch (1 mm) used to improve reliability against dirt particles or eccentric loading. Despite larger effective pitch (1.4 mm), typical serviceability limit of 0.3% drift was satisfied for both structural systems.
4. One unique feature of the ratcheting device is that the dissipator deforms solely in tension, even when subjected to full displacement cycles. Thus, only the monotonic (not cyclic) backbone curve is needed for numerical modelling. A good match was obtained with the simulated frame hysteresis.

These studies highlight the versatility of ratcheting devices to create highly dissipative systems across various structural systems and materials. By addressing the pinching, traditional systems with limited ductility (i.e., very slender braces and timber shear walls) can be transformed into structural systems of the highest performance class. They are inherently efficient since they do not require buckling restraints nor substantial post-tensioning. Further research on the dissipator combination (e.g., friction) would be helpful to ensure adequate cumulative deformation over multiple earthquake events.

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