17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

A PINCHING-FREE CONNECTOR FOR TIMBER STRUCTURES AND ITS APPLICATION IN A ROCKING SHEAR WALL

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Keywords: pinching; ductile timber connection; rocking shear wall; flag-shaped hysteresis; ratchet.

Abstract

Conventional timber connections employ steel fasteners such as nails, bolts and dowels. Traditionally, these have been designed to yield in bending to provide a degree of ductility and stiffness to the connections, and thus, to the structure. However, the combination of steel yielding failure and crushed timber fibres at the steel-wood interface results in increasing amounts of slack (or looseness) in the connection. Although this is not an issue for monotonic loads, it can severely impair the performance during earthquake loads which are cyclic by nature.

Under such circumstances, the full capacity of the connection cannot be mobilised immediately. This is because the fasteners are required to bend and conform to the curved shape of the fastener holes left behind from the previous loading cycle. When the fasteners have traversed the elongated hole and fully contact the wood fibres along their shanks, the connection becomes fully engaged and achieves the backbone curve. This gain in strength however is very gradual and occurs only after a relatively large amount of deformation. Such a delay in response manifests in a pinched hysteretic loop, which is associated with degradation of stiffness and strength.

Because of this pinching phenomenon, engineers have attempted to avoid and to prevent the possibility of Mode 1 failure. This is because pure embedment/crushing creates the largest cavity, and therefore results in a sudden loss of stiffness. However, if pinching is prevented, Mode 1 can also be an extremely ductile form of failure as its behaviour closely resembles an elastic-perfectly plastic backbone curve. Therefore, this failure mode possesses high stiffness and a predictable capacity, potentially leading to a reduction of over-strength factors. A new pinching-free connector (PFC) was developed at the University of Auckland to take advantage of these benefits.

The PFC is a ratcheting device that resists tensile loads via controlled crushing of timber fibres. The ratcheting action eliminates the slack that forms from crushed timber. In doing so, the connection can remain free of slack as the fastener(s) is/are always engaged with the timber. At the connection level, the tensile behaviour is characterised as a flag-shaped hysteresis with a constant load plateau and zero resistance to re-centring. Component tests were performed to verify the performance of the PFC. A ductility of 10 was achieved, while successfully eliminating pinching.

One potential application of the PFC is for hold-downs in rocking timber walls. The characteristics of the PFC lend itself to a rocking wall that has a stiff and predictable resistance to any off-centre loading. Upon unloading, the device does not resist in compression as it is tension-only – this allows the wall to re-centre freely. Numerical simulations of a shear wall model show that the PFC reduces peak displacements by a factor of 3 as a conservative estimate. This was mainly due to effective dissipation of seismic energy, including that from ground motion pulses. A high stiffness also helped to ensure elastic behaviour during the smaller cycles. Together, these led to a reduction of the imparted seismic energy by a factor of 5. The PFC has the potential to alter the traditional design philosophy of using many small-diameter fasteners, to few and large ones and thus creating new possibilities for low-damage timber connections.

1. Introduction

The philosophy when designing timber connections is to use many small-diameter fasteners such as nails, screws and bolts. Under extreme loads like earthquakes, the slenderness of the fasteners encourages flexural yielding at the shear connections. This ensures that a minimum amount of ductility is present as the joint absorbs the seismic loads on the structure.

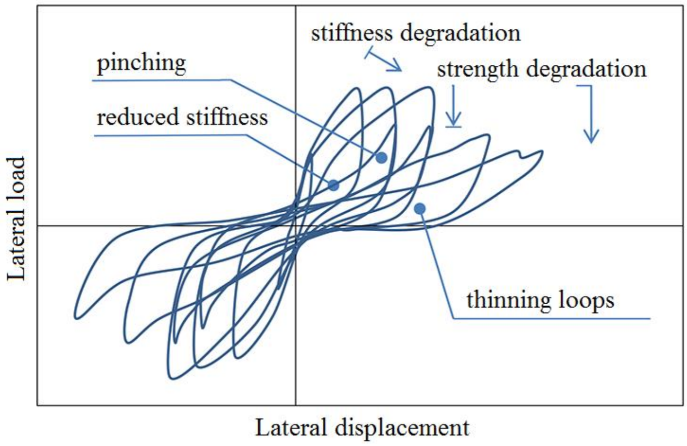

Fig. 1 – Pinching behaviour in common timber connections [1].

However, even if brittle failure of the timber is prevented at the joint, the yielding failure of the timber/fastener combination will include an increased amount of pinching at every subsequent cycle, as shown in Fig. 1. Designers have accepted this pinching behaviour as a characteristic of timber connections resisting cyclic loads. A new connector has been developed to prevent this pinching behaviour in timber connections.

2. Current Design Approach

Building structures are occasionally subjected to extraordinary loads, such as during earthquakes. Structures are presently designed to cope with these loads without catastrophic failure. However, damage to the structure or parts of the structure is inevitable, and to an extent desirable or intended. In particular, predictable fracturing or plastic yielding of building components or materials can be intended to absorb the energy of an event, thereby reducing peak loads or displacements and thus lessening the risk of more significant failures.

One example of this type of predictable damage occurs in joints between wooden members and other parts of a structure. Where wooden members are connected to a flange or flanges by fasteners such as bolt or bolts, extreme forces can lead to crushing of wood against the fastener. The connection resistance associated with these different ductile failures has been well studied since its introduction by Johansen [2]. Fig. 2 shows three possible modes of failure for a steel-wood-steel connection as a result of crushing and/or yielding.

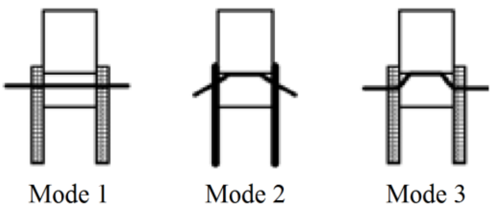

Fig. 2 – Failure modes in steel-wood-steel connections [3].

This crushing/yielding can be a significant energy absorber. However, in an event such as an earthquake which induces cyclic forces or displacements, the wood member may be forced to move alternately relative to the fastener. Movement-induced crushing in the first cycle opens up a cavity and allows a degree of "play" between the fastener and the wooden member. The fibre crushing is irreversible, so the crushed timber area does not provide an immediate response in subsequent cycles of the event.

This "slack" or "play" leads to a delay in the connection response, termed "pinching." The pinching means that the amount of energy available to resist earthquake excitation in subsequent cycles is limited. This is illustrated in Fig. 3 for a tension-only connection.

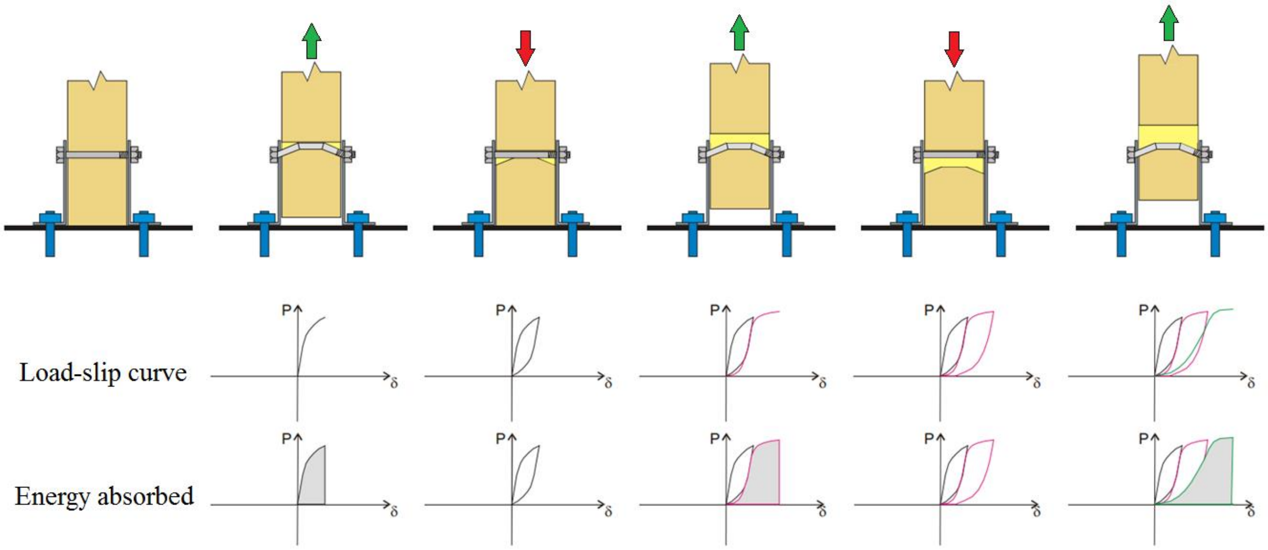

Fig. 3 – Cyclic behaviour of conventional timber connections that exhibit pinching.

After the 2010 Darfield earthquake in New Zealand, Beattie reported that timber-framed residential houses may have suffered reduced stiffness and increased sensitivity to high winds and minor tremors as a direct result of the earthquake [4]. This could be attributed to pinching in the timber joints, whereby greater deformations become necessary before significant resistance can be mobilised to absorb energy imparted to the structure.

3. Proposed Pinching-Free Connector

A novel connector was developed at the University of Auckland to overcome the pinching behaviour [5]. The concept is based on the principle that the "play" or "slack" that occurs at every load cycle is absorbed/eliminated. Essentially, the timber fastener can yield or remain in the elastic range but the bulk of the seismic energy is absorbed through crushing of the timber fibres. The displacement resulting from this fibre crushing is absorbed at every loading cycle. This offers the advantage that the joint fasteners, even in their bent state, are available to mobilise the full energy-absorbing capacity of the embedment of the timber. This is shown in Fig. 4 for one of the PFC concept.

To achieve a slack-free connection, the PFC creates permanent engagement between the bolts and the timber. It relies on a ratcheting mechanism consisting of load-transferring wedges (as shown in Fig. 5) and they function in a similar manner as a door-stopper wedge. In this case, the spring-loaded wedges can travel during the unloading cycles, and thus reset the location at which load begins to transfer on the loading cycles. By having the wedges travel instead, the bolts are no longer required to traverse across elongated holes on loading cycles. The PFC becomes unaffected by any slack generated, since the bolts will never separate from the timber at the loaded contact surface.

With the advantage of removing the play or slack in the connection, the governing resistance failure mode becomes Mode 1 of the European Yield Model. Although the design of the joint could be made with slender or stocky fasteners, the ultimate amount of energy absorbed at every cycle would be controlled by the Mode 1 resistance.

In the case of a PFC joint with small diameter fasteners, the fasteners would deform and yield according to the EYM and exhibit a Mode 2 or Mode 3 deformation behaviour. However, as the “slack” is not an issue anymore, the fasteners will continue to resist any additional loading resulting from the imposition of additional deformation at subsequent cycles.

One important requirement of the PFC is that there is sufficient resistance against one of the possible brittle failures (either row shear or group tear-out), even after a large amount of embedment failure [6]. This is possible if the end-distances and bolt spacings in-row are large or if there are screws perpendicular-to-grain to prevent longitudinal shear failures.

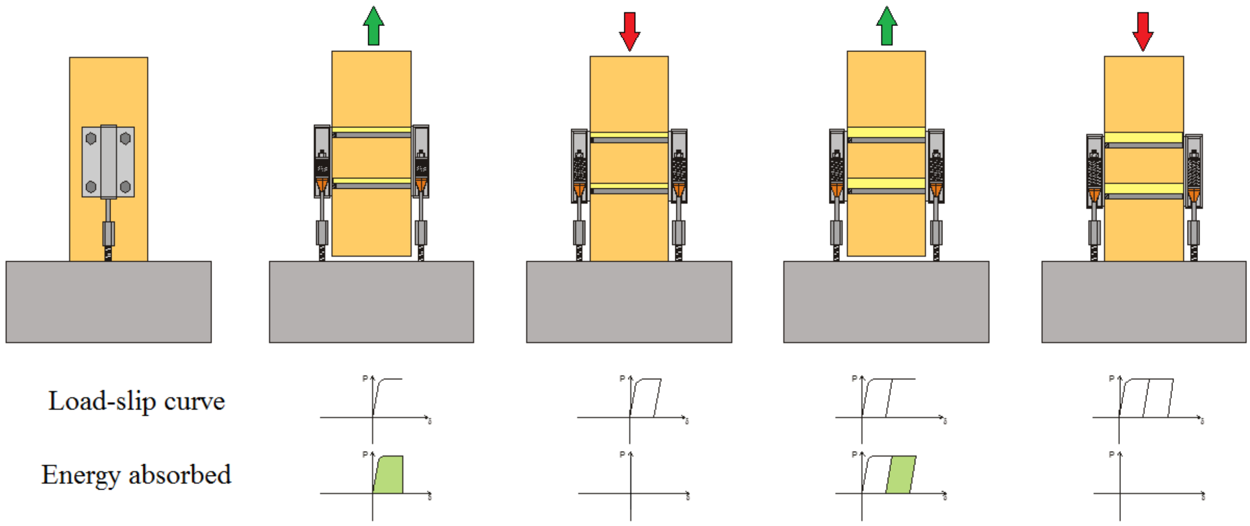

Fig. 4 – Proposed Pinching-Free Connector (PFC) and its cyclic behaviour.

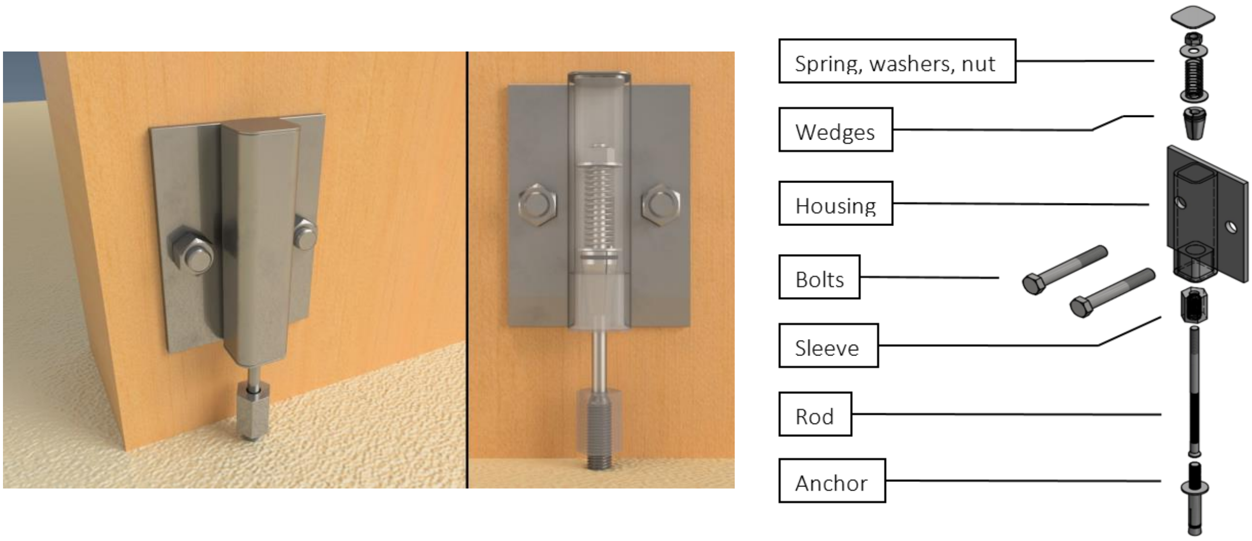

Fig. 5 – A render and an exploded view of the PFC.

4. Experimental Demonstration

Experimental tests were performed to verify the ability of the proposed connector in eliminating pinching and to absorb the optimum amount of seismic energy on every cycle. Fig. 6 depicts two configurations of the PFC tested – one designed for pure crushing and the other for a mixed-mode failure to happen. The goal in doing so was to demonstrate different behaviour possible with the PFC, as Table 1 shows. Finally, a conventional bracket hold-down was also tested to compare against the PFC.

Fig. 7 shows the load protocol that was applied in these tests. For the PFC, small-cycle deformations can accumulate rapidly because of their ratcheting action. This means that the PFC could undergo more crushing overall than the conventional brackets, all during the small-amplitude cycles. So, for these quasi-static tests the total ratcheting distance was designed for approximately 30 mm of deformation.

Table 1 – Summary of connections tested.

Test #	Connection	Fasteners	Pinching Occurs	Bolts Yield	Timber Crushes
Test 1	Conventional	6-M10 – Grade 4.8	Yes	Yes	Yes
Test 2	PFC	4-M10 – Grade 8.8	No	Yes	Yes
Test 3	PFC	2-M16 – Grade 8.8	No	No	Yes

Fig. 6 – Close-up views of the connections tested. Tests 1 to 3 from left to right.

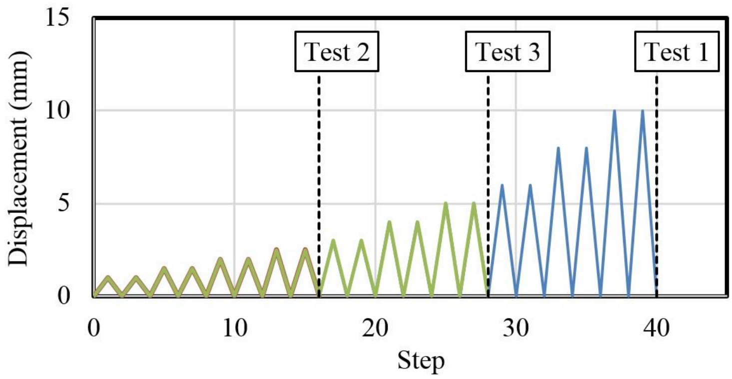

Fig. 7 – Load protocol for tests 1 to 3.

Fig. 8 shows the resulting load-deformation graphs and corresponding specimens post-test. As expected, the hysteresis loops in Test 1 are significantly pinched, whereas Tests 2 and 3 did not show any signs of pinching. Instead, they produced high stiffness on each reloading cycle, at values approximating the elastic deformation of the wood. This confirmed that the PFCs provided permanent engagement of the fasteners.

As the fasteners became stronger and stockier from Tests 1 to 3, the initial stiffness of the backbone curves also improved. While Test 1 (conventional connection) required relatively slender fasteners to minimise the severity of pinching, the PFCs were not restricted by this limitation. As pinching was not an issue, higher deformations (e.g. ductility of 10) became possible with the PFCs. Both PFCs achieved their ultimate embedment loads at approximately 12 mm and 6 mm respectively – the first after significant bolt bending, and the latter without any bolt bending. It is interesting to observe that Test 2 began with a Mode 3 failure but transitioned to Mode 1 eventually, as the fastener plastic capacity was mobilised and surpassed the timber embedment capacity. This transition of failure modes allowed the PFC to achieve its load plateau.

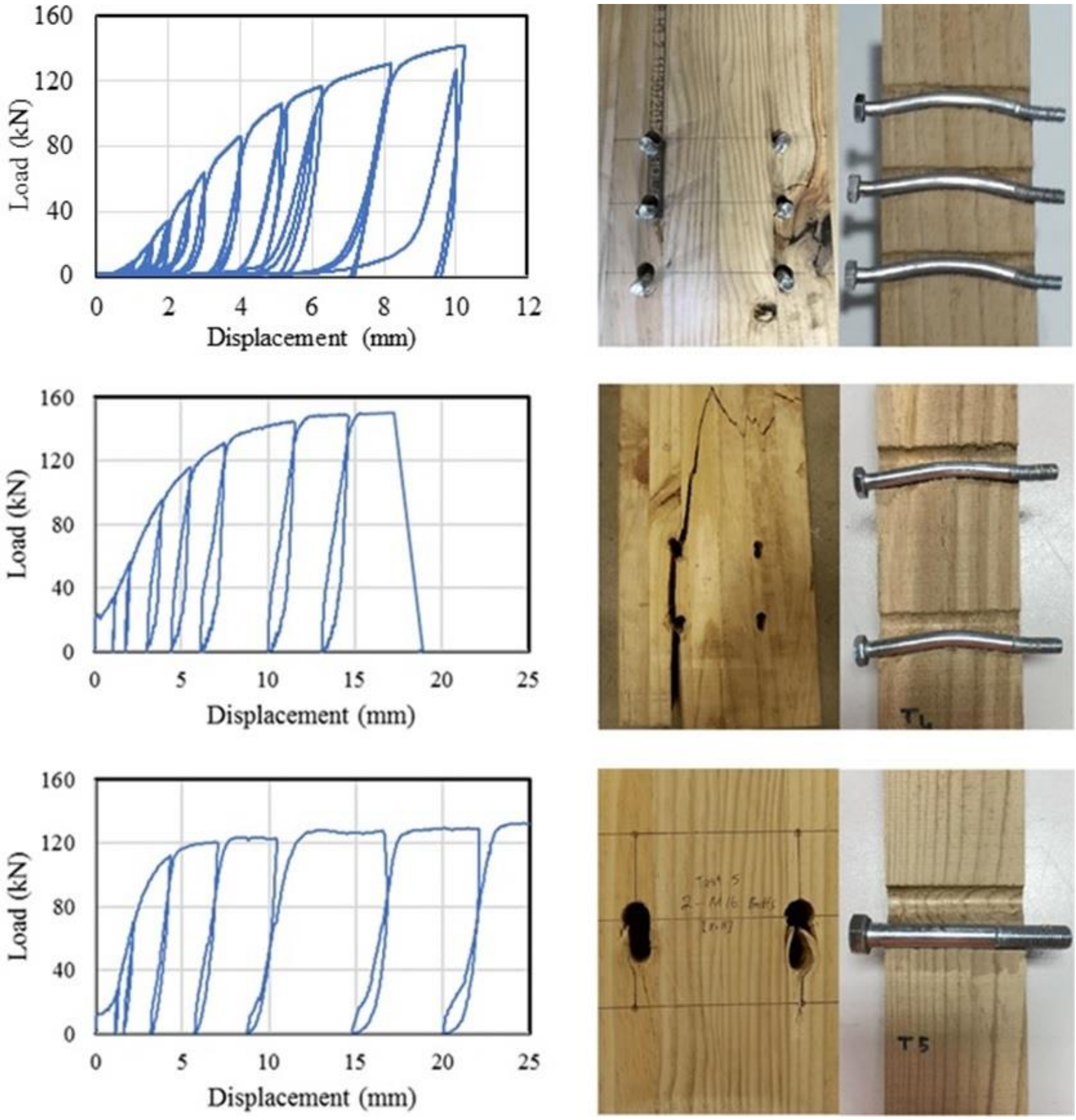

Fig. 8 – Load-deformation curves and pictures of the specimens post-test.

Some hardening was observed in Test 3 which could be attributed to densification of the compressed wood fibres. There was also an initially low stiffness, which was caused by excessively over-sized holes which were 2 mm larger than the fastener diameter. This shows the importance of proper pre-drilling and installation to provide a stiff and ductile timber connection.

A re-usability advantage is also presented by a PFC with stocky bolts, which avoids any bending and thus damage to the steel parts. Although the timber fibres are crushed, the steel components of the PFC remain damage-free. If the crushed timber is repaired, the device can be 'reset' and re-used after consuming its designed travel distance. Alternatively, sufficient travel length could be provided to last the entire life of the structure. By doing so, there would be no need to reset the device nor repair the crushed timber.

5. Application in Shear Walls

To investigate the applicability of the PFC in a seismic load-resisting system, ground motion simulations were performed for a shear wall equipped with the PFC. The model consists of a standard-sized wall that is 1.2 m wide by 2.7 m tall. It sustains a seismic (lateral) mass of 10 tonnes that are distributed along the top of the wall. A gravity load of 12 kN (i.e. 10 kN/m) was also applied to approximate the dead load from the upper floor.

At the base of the wall, lateral restraints were placed at the bottom corners of the wall to serve as shear keys and induce rocking in the wall. Gap elements, also located at the corners, simulate the floor beneath the wall and prevent penetration into the ground. As for the hold-downs, one hold-down was placed at each end with sufficient clearances from the side- and the bottom- edges, as required to avoid brittle failures in practice. A diagram of the wall model is shown in Fig. 9.

In these simulations, two types of hold-downs were compared: one representing a conventional timber connector (CTC) and the other representing the proposed pinching-free connector (PFC). These were based on the connectors used in Test 1 and Test 3. However, both connections were assigned the same ultimate capacity of 150 kN in these simulations, as shown in Fig. 10.

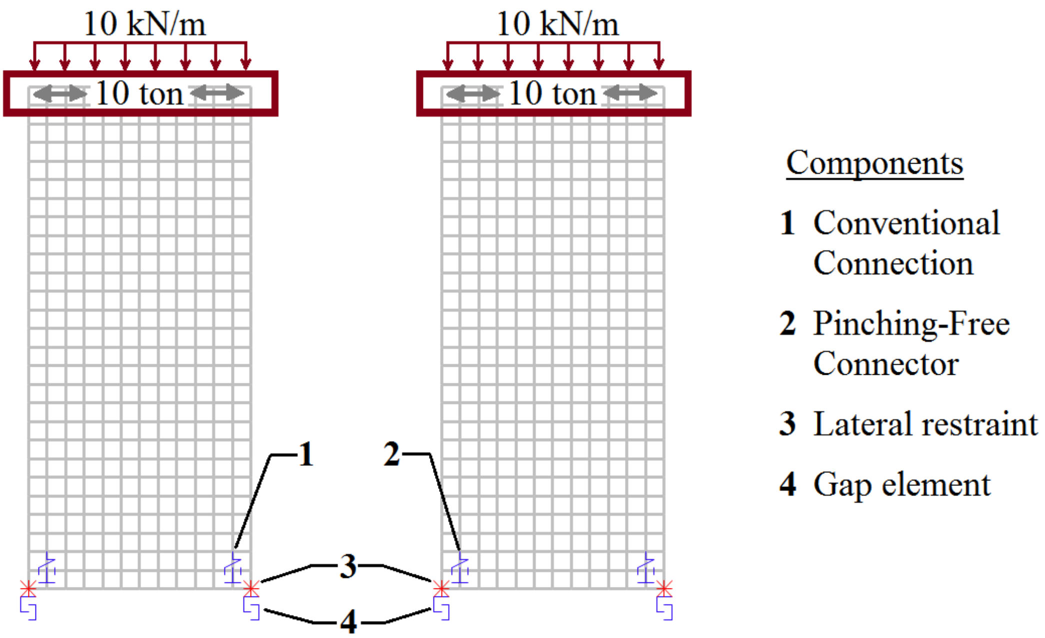

Fig. 9 – Shear wall models equipped with conventional hold-downs (left) and with PFCs (right).

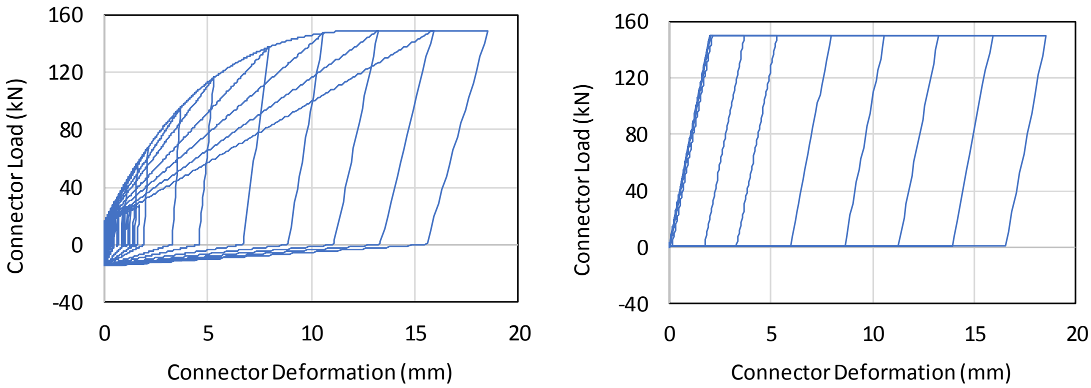

Fig. 10 – Hysteresis of the hold-downs. Left: Conventional connection. Right: PFC.

For the PFC, friction-spring elements were used to idealise the tension-only behaviour. It has near elastic-perfectly plastic backbone curve, and negligible resistance to restoring/re-centring as the PFC does not resist compression. For the conventional hold-downs, a multi-linear plastic element (with pivot hysteresis) was used to model the effects of pinching and stiffness degradation. More details on this method can be found in [7] which validated the technique for nail models. However, as the present connection is a bolted one, there is an important difference in that the fastener does not experience withdrawal. A slight modification to the technique was made to better simulate the hysteresis of a bolted connection.

$$F = F_f + \begin{cases} (F_0 + K_1\delta)\left(1 - e^{-\frac{K_0}{F_0}\delta}\right) & \delta \le \delta_{ult} \\ (F_0 + K_1\delta_{ult})\left(1 - e^{-\frac{K_0}{F_0}\delta_{ult}}\right) & \delta \ge \delta_{ult} \end{cases} \tag{1}$$

Eq. (1) shows a Foschi backbone curve that includes an initial slip force. The purpose of this is two-fold – the first reason is to model the friction of the steel side-plate, which occur due to the tensioned bolts. This is present in bolted connections but much less so in nailed connections. The second and more important reason is to simulate a proper unloading stiffness with the pivot model. This is only possible if the initial stiffness is higher than the unloading stiffness, so that the two branches eventually converge at a common pivot point as required by the pivot model. The reader is referred to [7] and [8] for more detailed information regarding the pivot model. Specific values used to parameterise the connections are provided in Table 2.

Table 2. Parameters used to model the connections.

Conventional Connection				Pinching-Free Connection		
F_f	15	kN		k_i	75	kN/mm
F_0	230	kN		k_l	0.001	kN/mm
K_0	30	kN/mm		k_u	0.00001	kN/mm
K_1	-5	kN/mm		pcp	-149 998	mm
K_2	0	kN/mm		u_{slip}	2	mm
K_3	75	kN/mm		F_{slip}	150	kN
δ_{ult}	12	mm				

Ten ground motions from the PEER NGA-West2 database were used to provide the input excitation. Each of them was amplitude-scaled in accordance with the New Zealand seismic standard, NZS 1170.5 [9]. The scaling was conducted on a period range of $0.4T_1$ to $1.3T_1$, and the target design spectrum corresponded to a site hazard factor of 0.4, site soil class D, and a return period of 500 years.

Fig. 11 shows the resulting time-histories and corresponding hysteresis of the wall for some of the ground motions. In all cases, the shear wall sustained smaller peak deflections when the pinching-free connectors were applied as the hold-downs. Two interesting observations are that the displacement demands were reduced substantially during the ground motion pulses; also, the wall appeared to vibrate at higher frequencies in general.

The first observation can be explained by the nature of the PFC that provides relatively high stiffness and dissipation in response to ground motion pulses. This high stiffness also helps to explain the second point, where the wall stays in its elastic range while vibrating at higher frequencies.

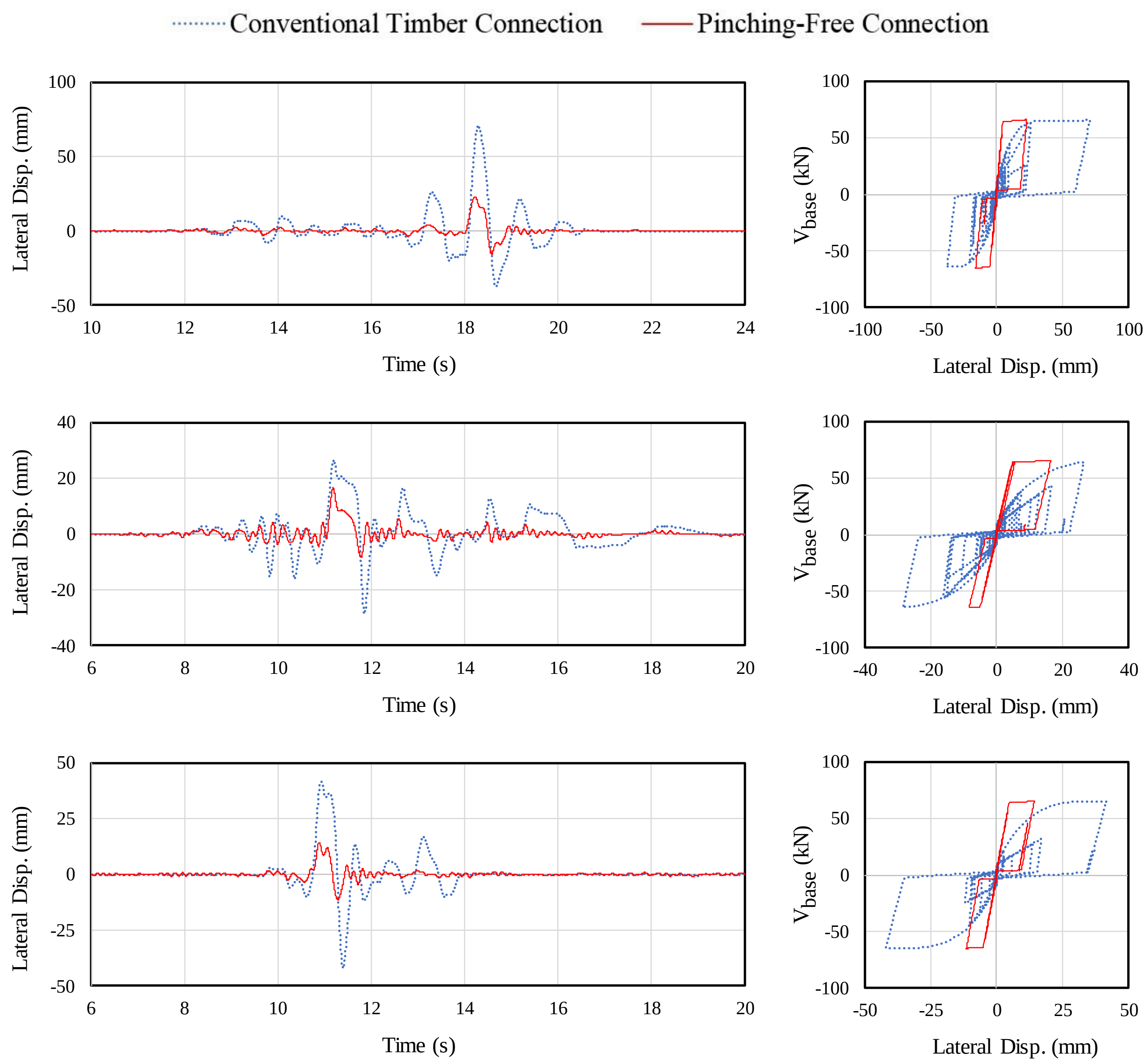

Fig. 11 – Time-histories and wall hysteresis for the Chi-Chi, Christchurch and Duzce ground motions.

Fig. 12 shows a time-series of the energy input and dissipated for the time-histories corresponding to Fig. 11. Two noteworthy points from these graphs are: there is much less energy input and energy dissipated with the PFC; there are also sharper changes in both energy input and dissipated for the PFC.

These differences lie in the response of the PFC which is mainly elastic, except during the pulses in ground motions. When the pulses occur, the PFC effectively dissipates the burst of energy, as seen from a sharp step/rise in the hysteretic dissipation which coincide with the timing of the pulses in Fig. 11. During smaller cycles however, the PFC remains elastic so that most of the energy is dissipated via elastic modal damping.

On the other hand, the conventional connection possesses lower stiffness due to pinching as well as softening in the backbone curve. This means that hysteretic dissipation occurs during the smaller vibrations early on, as Fig. 12 shows. Being more prone to higher amplitude vibrations, the conventional connection receives greater quantities of seismic energy which are consistently 5 times higher than those of the PFC.

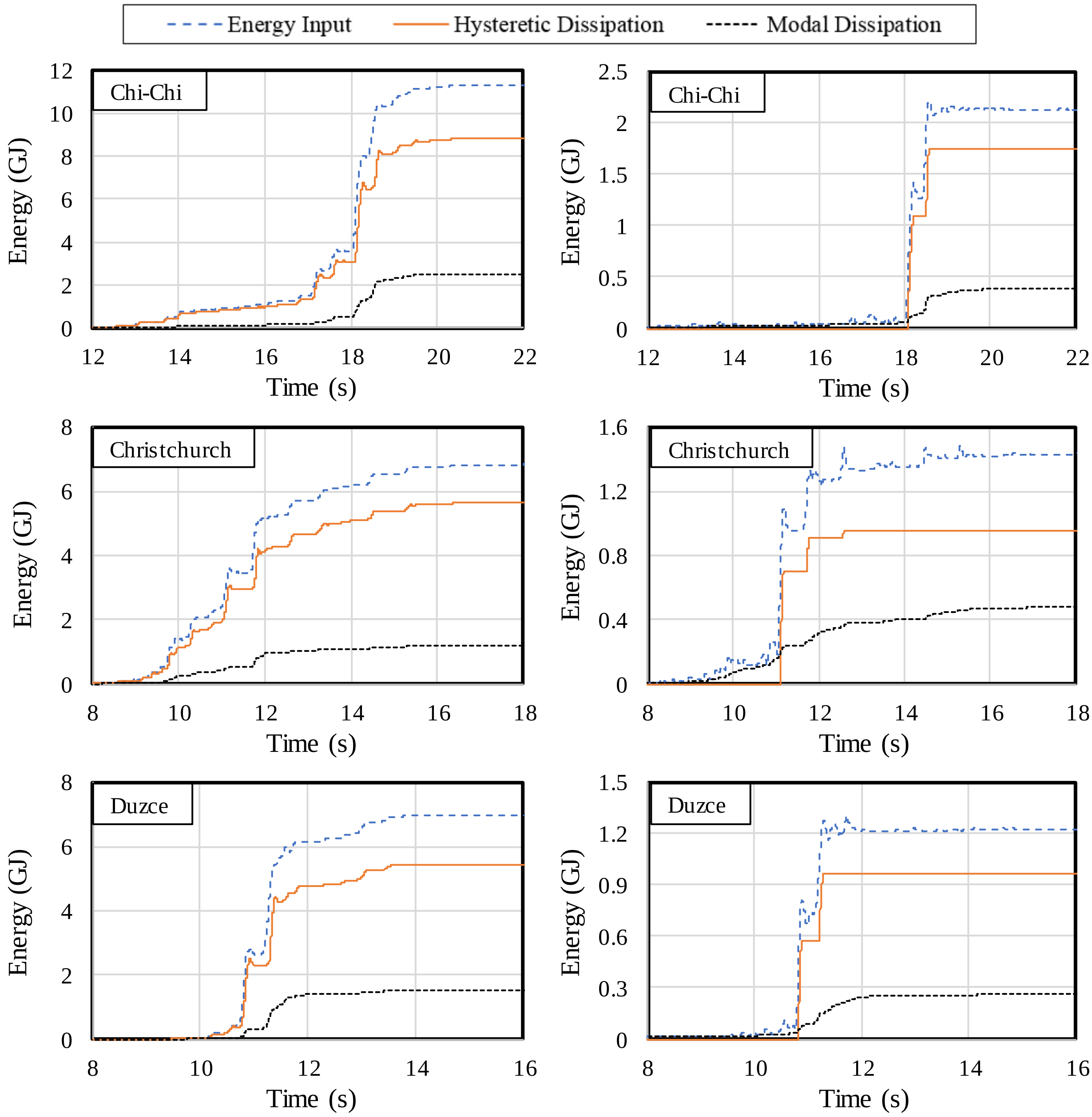

Fig. 12 – Energy gained/lost corresponding to the 3 time-histories in Fig. 11. Left: Conventional. Right: PFC.

Table 3 – Summary of input excitations and resulting peak displacements.

Ground Motion Information					Peak Displacement (mm)	
Event	Station	Year	Scale Factor	Arias Intensity	Conventional (CTC)	Proposed (PFC)
Chi-Chi	CHY080	1999	0.85	5.0	71.0	23.0
Christchurch	Botanical Gardens	2011	1.19	3.8	28.4	16.5
Darfield	GDLC	2010	1.06	5.1	45.2	15.2
Duzce	Bolu	1999	1.11	3.0	41.8	14.4
Imperial Valley	El Centro Differential Array	1979	1.16	2.9	24.6	7.9
Kaikoura	WDFS	2016	0.61	6.2	14.0	8.4
Kocaeli	Duzce Meteorological Station	1999	1.39	2.7	37.4	7.9
Landers	Lucerne	1992	1.09	8.3	14.0	8.7
Loma Prieta	LGPC	1989	0.97	7.4	43.3	11.8
Northridge	Saticoy Street	1994	1.10	5.6	34.2	9.5

Table 3 summarises the responses of the shear wall in terms of peak roof displacements. Although the conventional connectors were modelled in a conservative manner, there still appears to be a substantial difference in performance between the PFC and the conventional hold-downs. On average, the PFC reduced peak displacements by a factor of 2.9 times, which is close to the value of 3.0 found in a previous (less conservative) study [10].

Conclusions

The traditional philosophy when designing timber connections is to use many small-diameter fasteners. By doing so, the fasteners can yield in flexure and afford some ductility to the connection. However, timber is irreversibly crushed in the process and opens up a cavity. The elongation of fastener holes creates "slack" in the connection and leads to pinched hysteresis loops during cyclic loading. This pinching effect severely limits the amount of stiffness, ductility and dissipation available to the connection.

A new connector, called the pinching-free connector (PFC) was developed to overcome this pinching issue. Component tests were performed on the PFC and on a conventional connection for comparison. The tests verified the ability of the PFC to eliminate pinching while providing high stiffness and ductility at the same time when stocky bolts are used.

Although this contrasts with the traditional design approach, the advantages of the PFC were highlighted in ground motion simulations of a shear wall application. With the PFC, there was a consistent reduction in peak displacements by a factor of 3. This is due to high inelastic dissipation of seismic energy during pulses, and also a high stiffness that resulted in an elastic response at other times. The combined effect was a reduction in the quantity of seismic energy imparted to the structural model equipped with the PFC.

Acknowledgements

The authors would like to acknowledge Mark Byrami and the University of Auckland for providing the facilities and technical expertise to conduct the experimental tests.

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