Pinching-Free Timber Connector

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ABSTRACT

The philosophy when designing timber connections is to use many small diameter fasteners in order to ensure that a minimum amount of ductility is present and that the joint will absorb the seismic loads on the structure. 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. Designers have accepted this pinching behavior as a characteristic of timber connections resisting cyclic loads. In the paper, a new connector is presented that prevents this pinching behavior in timber connections. The main principle of the connector is based on eliminating the "slack" that occurs at every load cycle. This offers the advantage that the joint fasteners, even in their bent state, can mobilize the full energy-absorbing capacity of the embedment of the timber. In the absence of slack, the governing failure mode becomes Mode-I of the European Yield Model regardless of slender or stocky fasteners used. An experimental demonstration was conducted to show that slender fasteners cross-over from failure Mode-II/III initially to Mode-I eventually, attaining the load plateau as pinching was eliminated with the PFC. With stocky fasteners, the response of the connection on every loading cycle was repeatedly stiff and at a consistent load. In this configuration, a displacement ductility of 10 was achieved. This connection was compared to ordinary brackets in numerical simulations of a rocking shear wall subjected to ground motions. The PFC reduced peak displacements by a factor of 2.8 to 3.2, and post-peak vibrations were substantially muted. This contrasts with the large swings in displacements of the "loose" bracket connection possessing slack. This connector has the potential to alter the design philosophy of using many small dowel-type fasteners in timber connections to offer a ductile connection.

Keywords: Seismic, timber, connections, pinching, ductile.

INTRODUCTION

The philosophy when designing timber connections is to use many small-diameter fasteners in order to ensure that a minimum amount of ductility is present and that the joint will absorb the seismic loads on the structure. However, even if brittle failure of the timber is prevented at the joint, the combination of yielding fasteners and crushed timber will result in an increased amount of pinching on every subsequent cycle, as shown in Figure 1. Designers have accepted this pinching behavior as a characteristic of timber connections resisting cyclic loads.

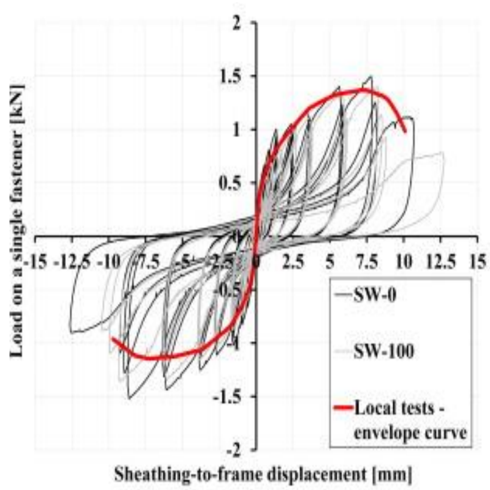

Figure 1. Pinched hysteresis loops observed in typical timber connections [1].

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 energy of an event, 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 structure. Where wooden members are connected to a flange or flanges by fastener(s) such as bolt or bolts, extreme forces can lead to crushing of wood against the fastener. The connection resistance associated with these different yielding failures has been well studied since its introduction by Johansen [2].

This crushing/yielding can be a significant energy absorber. However, in an event such as an earthquake which induces cyclic forces or displacement, 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. This play has a detrimental effect on the energy absorbency of the joint in subsequent movement cycles.

In timber buildings subjected to earthquake loadings, prior art structural joint solutions for resisting and damping seismic forces are mainly based on the yielding of the fasteners (bolts or dowels) in combination with crushing of the timber fibers by the fasteners. This achieves an amount of ductility and energy dissipation. However, earthquake loads are cyclic, with repeated loading and unloading. The fiber 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 Figure 2 for a tension-only connection.

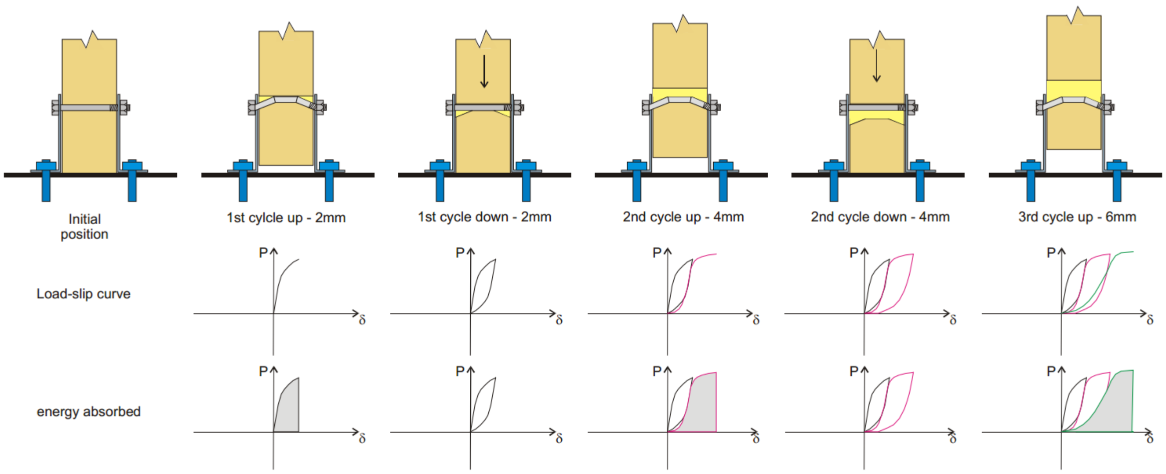

Figure 2. Pinching phenomenon observed in traditional bracket hold-down connectors.

PROPOSED PINCHING-FREE CONNECTOR

The PFC Concept

A novel connector was developed at the University of Auckland, New Zealand [3] to overcome the pinching behavior. The concept is based on the principle that the slack that occurs at every load cycle is absorbed or eliminated. With the advantage of removing the slack in the connection, the joint fasteners would always be engaged with the timber. 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 embedment strength of the wood, i.e. the Mode I resistance of the European Yield Model.

In the case of a PFC joint with small-diameter fasteners, the fasteners would initially deform and yield according to the EYM, exhibiting a Mode II or Mode III deformation behavior. However as bending progresses, the fasteners source additional bending strength from their plastic capacity. At some stage, the fastener bending resistance surpasses the embedment resistance of the wood so that the governing mode of failure crosses-over from Mode II/III to Mode I eventually. Essentially, the bulk of the seismic energy would be absorbed through crushing of the timber fibers. This offers the advantage that the joint fasteners, even in their bent state, are available to mobilize the full energy-absorbing capacity of the embedment of the timber. This is shown in Figure 3 for one of the PFC concept.

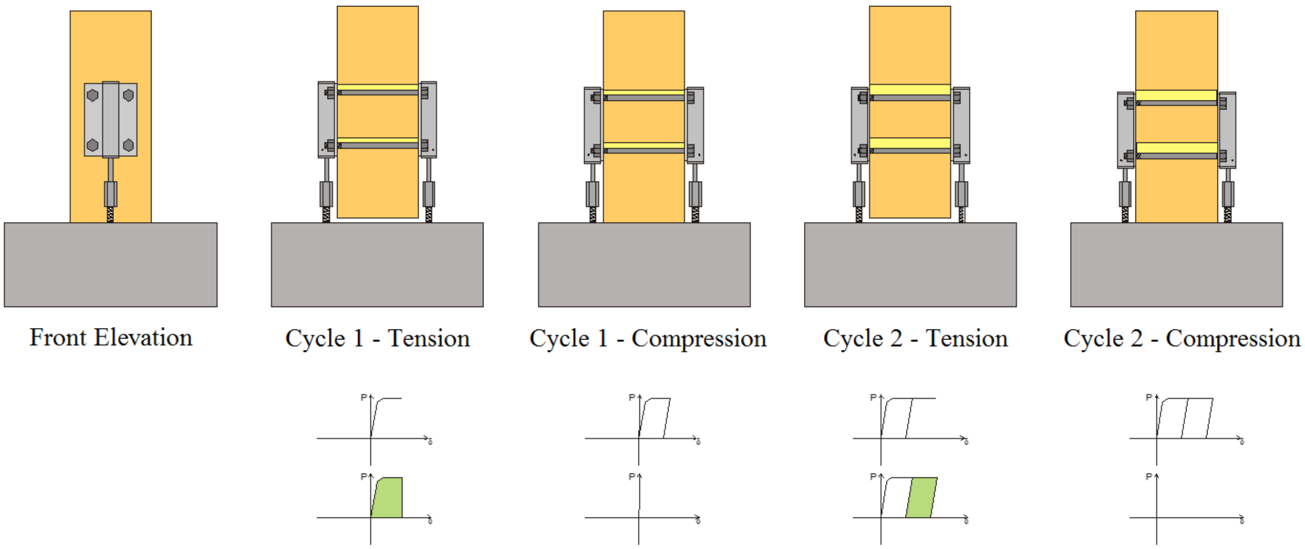

Figure 3. Slack is eliminated on each cycle by the proposed connector, providing a hold-down connection free from pinching.

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 [4]. 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.

The Prototype Device

Figure 4 illustrates a prototype of the PFC, where the device is applied as a hold-down for a timber member. There are seven main components as shown in the exploded view of Figure 4. The load path through these components is described as follows. When the timber member uplifts, the bolt holes in the wood bear against and crush under the stationary bolts to accommodate the uplifting movement. The uplifting or vertical shear force is transferred from the bolts into the housing weldment. Within the housing, the tapered barrel transfers the vertical force and at the same time, a horizontal reaction on the split-wedges due to the tapered wedge-barrel interface. This horizontal force clamps the split-wedges onto the rod, so that a tight grip on the rod can transfer the vertical tensile force through the rod and through the connecting sleeve into the foundation anchor.

During unloading, the timber member falls towards the ground along with the housing and the bolts as one unit, since the housing is tightly fastened onto the timber by the bolts. The bolt shanks remain in contact with the wood fibers at the bottom of their elongated bolt holes all the time. In doing so, no slack can form between the bolts and the contacting wood fibers. As the housing travels downwards, the tapered barrel departs from the split-wedges and any inward pressure on the wedges is released. This disengages the wedges from the rod in the absence of a horizontal clamping force. Subsequently, the wedges are dislodged and pushed by the spring down into the receiving barrel that is now at a lowered height. The wedges are again locked onto the rod, ready to provide tensile resistance on the next cycle of uplift. This describes the ratcheting behavior of the PFC.

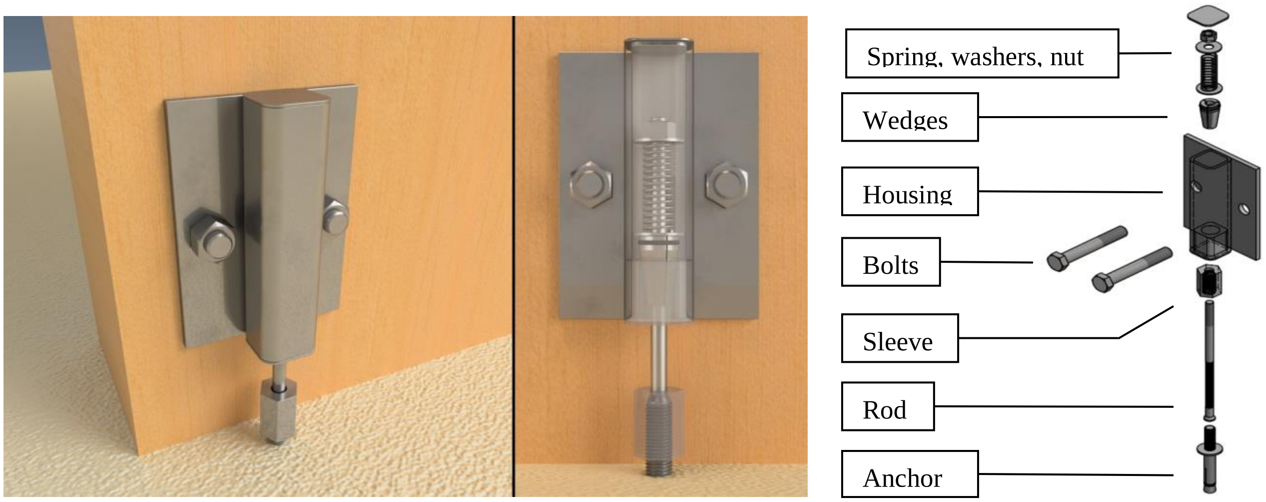

Figure 4. The pinching-free concept applied as a hold-down for rocking shear walls.

EXPERIMENTAL DEMONSTRATION

Test Setup

The test programme comprised of three tests to demonstrate the various behavior possible with the PFC. In the first test, standard steel brackets were used with 6-M10 low-strength bolts (as per Table 1) to represent the traditional design approach to ductile connections and in so doing, demonstrates the pinching problem associated with this approach. The aim of the second test was to eliminate this pinching by applying the PFC with fewer but higher-grade bolts. By using this configuration of bolts, the extent of deformation in the bolts was more controlled. This prevented premature failure of the bolts at the threaded end (nut-side) that can occur due to reduced cross-sections, resulting from the stress concentrations imposed on the fastener by the steel plate's sharp edges. As the bolts no longer govern the capacity of the connection, the ultimate embedment strength of the wood could be mobilized. In the third and final test, the fewest number of bolts were used, albeit the largest in diameter. Without any yielding in the bolts, this test examined whether a pure Mode 1 behavior could be achieved without any pinching.

Figure 6 depicts the three types of connections tested. In all cases, the steel side-plates were all similarly sized and positioned on the wood. Figure 7 shows the loading protocol applied on the wood specimen. The maximum displacements of the MTS loading arm were smaller for the PFC tests because of their ratcheting nature, which accumulate rapidly all of the small-cycle deformation in the absence of slack. This behavior is shown in Figure 7.

Figure 5. Close-up views of the connections used in Tests 1, 2 and 3.

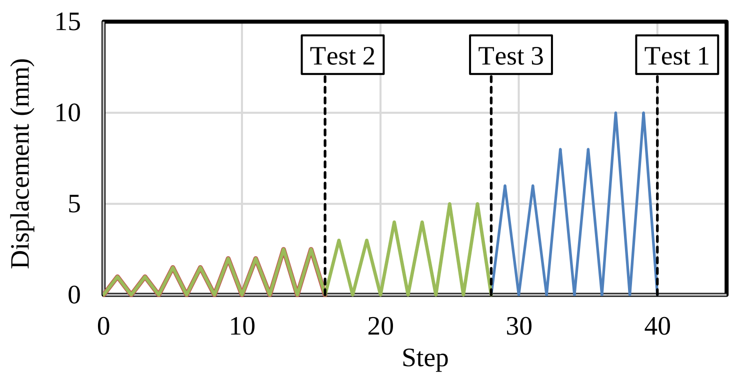

Figure 6. Load protocol for Tests 1, 2 and 3.

Table 1. Schedule of tests.

Test #	Connection	Fasteners	Pinching Occurs	Bolts Yield	Wood Crushes
Test 1	Brackets	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

Test Results

Figure 7 shows the load-displacement curves and pictures of the corresponding specimen at failure for each test. Observations from Test 1 show the greatest bending of bolts and an increasing amount of slack on each loading cycle as deformation progresses. A relatively slower gain in strength (backbone curve) was also noticeable as the full embedment capacity could not be reached even after 10 mm of deformation. This highlights the issue of connections with 'many small-diameter' fasteners in that a steady and reliable capacity is difficult to achieve without large deformation which is associated with pinching. This connection lacked a consistent stiffness and failure strength.

Pinching was eliminated in Test 2 which utilized the PFC. Fewer bolts were used in this connection, but less bending was observed as they had higher yield strengths. As pinching was no longer an issue, even larger displacements could be achieved without any loss of stiffness. Furthermore, the connection resistance could reach a plateau of 150 kN as the full embedment capacity of the wood was achieved. In this case, the test was terminated prematurely due to brittle failure of the wood.

Test 3 applied the PFC with two large-diameter, high-strength bolts. This is the exact opposite of the current design philosophy to use 'many small-diameter' fasteners (as in Test 1). However, the full embedment strength could be achieved much earlier as indicated by the plateau in Figure 7 while maintaining a high ductility capacity. On each loading cycle, the connection provided a stiff and immediate response in the absence of pinching. The stiffness arose from friction initially but eventually was governed by the elastic deflection of the wood. The caveat for high stiffness on the very first cycle is that the device should be screwed tightly into the anchor to ensure that any slack is already eliminated when the device is engaged. This connection – while different from the traditional approach – could achieve greater ductility (10 in this test) without any loss of strength or stiffness.

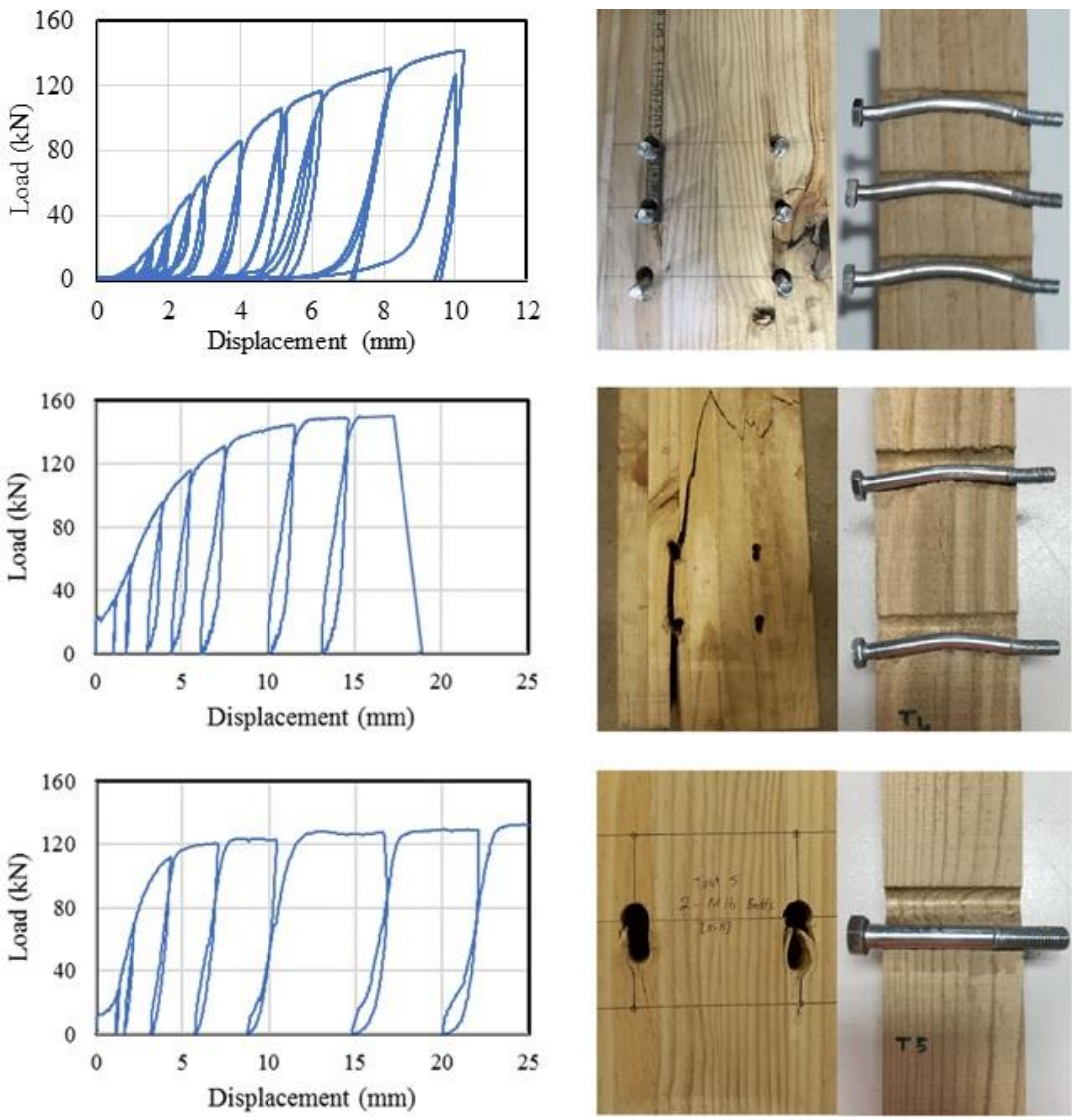

Figure 7. Hysteresis and specimen of the three connections tested. Note that the x-axis scales are adjusted for clarity.

SIMULATING SEISMIC PERFORMANCE WITH THE PFC

Simulations were performed using the SAP2000 software package to examine the behavior of a rocking shear wall equipped with the PFC. In this example, a timber shear wall that is 1200 mm wide by 2700 mm tall was considered as the lateral-load resisting member (Figure 8). A lateral mass of 10 tons was assigned to the top of the wall. Gap elements were used to simulate the foundation, while horizontal restraints were assigned as shear keys at the toes of the wall.

Friction-Spring Damper link elements that could be calibrated to work only in tension were used to model the ratcheting behavior of the PFC. The backbone curve was idealized from Test 3 (Figure 7) as an elastic-perfectly plastic shape. Crushing was assumed to initiate after 2 mm of elastic deformation. To model the ordinary brackets, multi-linear plastic elements [5] were connected in series to elastic cable elements. The cable elements made it possible to model the slack that occurs in ordinary brackets due to elongated bolt-holes. The backbone curve of the plastic element was based on Test 1 (Figure 7). In both cases, the ultimate capacities of the connections were 150 kN.

Table 2 shows the ground motions obtained from the PEER NGA-West2 database and used as the input excitations. They were scaled to match the New Zealand design spectrum with a site hazard factor of 0.4, site soil class D and a return period of 500 years representing the ULS design level earthquake [6].

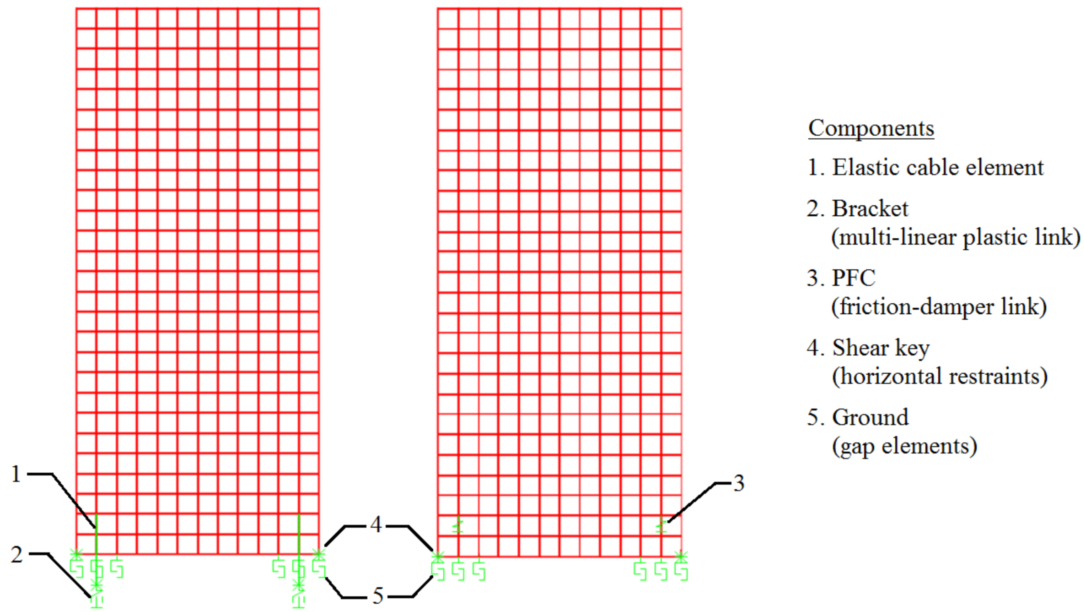

Figure 8. Shear wall models equipped with ordinary bracket connections (left) and pinching-free connections (right).

Table 2. Ground motions used as input excitation.

Event	Station	Year	Mw	Fault	Arias Intensity	Scale Factor
Christchurch	Botanical Gardens	21 Feb 2011	6.2	Reverse	2.7	1.08
Kobe	Takarazuka	16 Jan 1995	6.9	Strike-slip	3.9	0.88
Northridge	Saticoy Street	17 Jan 1994	6.7	Reverse	4.6	0.90

Table 3. Results of non-linear time history analyses.

Event	Peak Displacement using Brackets (150 kN)	Peak Displacement using PFC (150 kN)	Optimized PFC Capacity to Match the Brackets Peak Disp.	Optimized PFC Base-Shear Reduction Factor, k_μ
Christchurch	61.6 mm (2.3%)	22.3 mm (0.8%)	92 kN	3.6
Kobe	39.8 mm (1.5%)	14.8 mm (0.5%)	105 kN	1.9
Northridge	48.0 mm (1.8%)	15.0 mm (0.6%)	72 kN	5.0

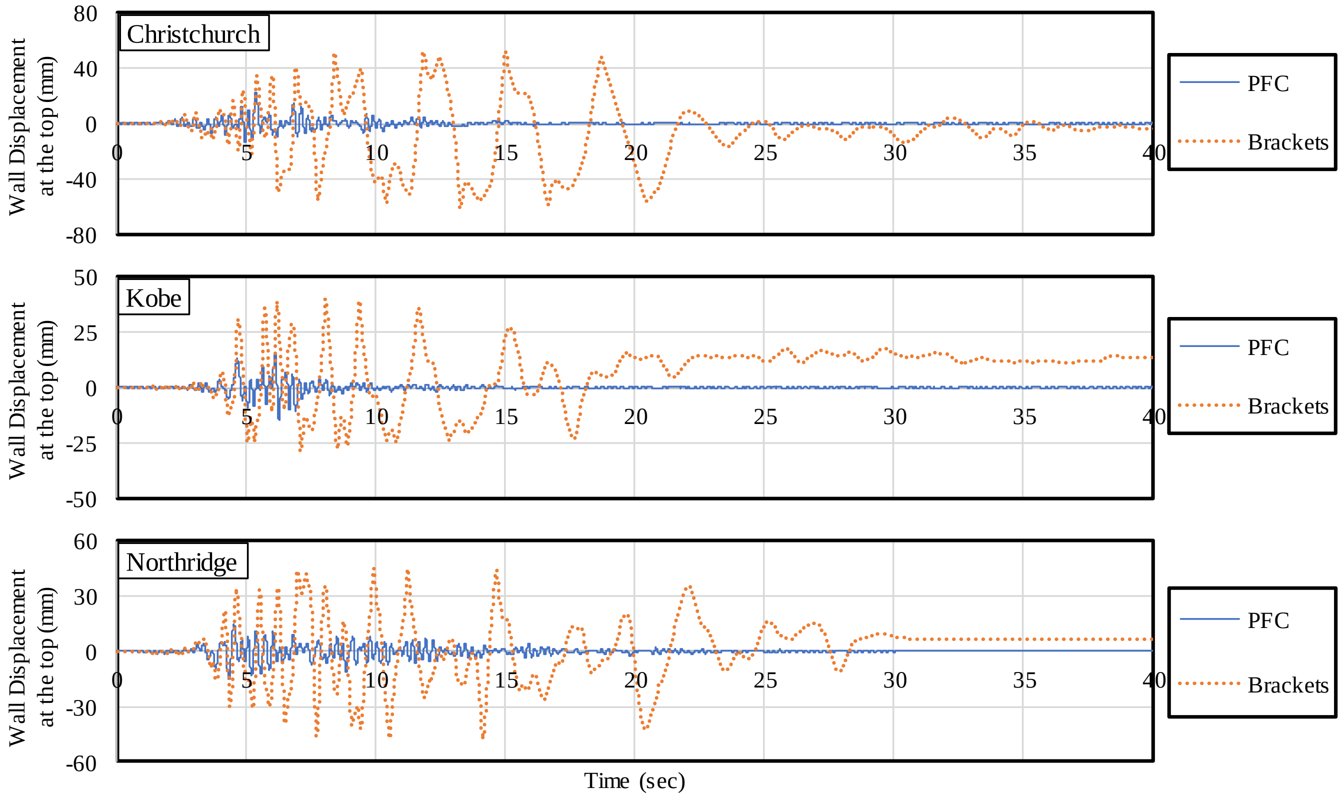

Figure 9. A comparison of displacement time-histories. Top: Christchurch; Middle: Kobe; Bottom: Northridge.

Figure 9 shows the resulting displacement time-histories. Table 3 shows that the peak displacements were smaller with the PFC as compared to the brackets by a factor of 2.8 to 3.2. Due to the presence of slack in the bracket connections, there were consistently large swings in displacements long after the peak acceleration demands were over, as expected from a "loose" connection possessing significant slack. In contrast, the wall equipped with the PFC underwent smaller-amplitude and higher-frequency vibrations, which resemble stiffer connections. This was expected because the PFC provides stiff and immediate resistance to any uplift (i.e. any movement that pushes the wall further off-center) and being a tension-only device, allows the wall to return to its upright position without any resistance. Hence, post-peak vibrations with the PFC were substantially smaller and mostly elastic.

Given the significant reduction in peak displacements afforded by the PFC, it may be overly-conservative to design PFC connections (based on peak displacements) with the same capacity as standard brackets. Instead, it may be possible to optimize or reduce the capacity of the PFC to achieve a given limit on peak displacements. Referring to the Christchurch excitation for example, if the peak displacement of 62 mm (i.e. 2.3% drift) was an acceptable response for the wall with traditional 150 kN brackets, then the same drift could be achieved by the PFC wall using a reduced PFC capacity of 92 kN.

For the optimized or reduced PFC capacities, elastic analyses were also performed to get the elastic base-shears. With these, the reduction in base-shears could then be calculated as the ratio between the elastic to inelastic base-shears. As shown in Table 3, the reduction factors ranged between 1.9 to 5.0. This shows that a non-negligible reduction in base-shear could be attained for inelastic design, by reducing or optimizing the PFC capacity while keeping peak displacements at acceptable limits.

The benefit of a reduced connection strength flows onto reduced structural member sizes as well, assuming that capacity design principles are adhered to. In addition, a predominant and predictable failure Mode 1 implies that smaller over-strength factors are possible because the connection strengths are well-defined by the embedment strength that plateaus relatively early. This may imply further cost savings for structures equipped with a pinching-free connection.

CONCLUSIONS

This paper presents a new pinching-free connector (PFC) for timber members resisting cyclic loading. An experimental demonstration was undertaken to verify that the PFC prototype could prevent pinched hysteresis loops in timber connections. In addition, an alternate configuration of fasteners was tested on the PFC to investigate the possibility of a low-damage pinching-free solution that is also more reliable and predictable in terms of performance. Ordinary steel brackets were also tested to compare and highlight some issues in the traditional approach to design. Finally, numerical simulations were performed to compare the potential benefits of the PFC as against standard steel brackets when applied as hold-downs in a timber shear wall.

Under repeated cycles of tensile loading, the bracket connection (with 6-M10, Grade 4.8 bolts) was shown to suffer from a relatively slower uptake in strength as well as poor cyclic behavior that exhibits pinching, i.e. delayed resistance due to the slack formed from previous cycles of deformation. In contrast, the PFC (with 4-M10, Grade 8.8 bolts) was able to eliminate pinching and at the same time achieve a load plateau. The load plateau indicates a transition from Mode II/III to Mode I of the European Yield Model, where the full timber embedment strength was eventually mobilized – even with bent fasteners.

For the final test, the PFC utilized an alternate configuration of fasteners of 2-M20 (Grade 8.8) bolts. Although this connection used the smallest number of fasteners, the resulting behavior from using strong and large-diameter fasteners was an outright Mode I resistance that mobilized the full timber embedment strength immediately and continuously. In the absence of pinching, this connection produced the stiffest and fastest uptake in strength that was repeated on every loading cycle. It exhibited a well-defined and predictable load-carrying capacity; and it also achieved an extremely ductile performance giving a displacement ductility of 10 without any loss of strength or stiffness.

The numerical simulations utilized 3 ground motions scaled as per the New Zealand Standard NZS1170.5. The results of a comparison between PFC and traditional brackets indicated approximately 3 times reduction in peak displacements as well as substantially muted post-peak vibrations, which were mainly elastic. In contrast, the rocking wall equipped with the bracket connections demonstrated large swings in displacements long after the peak ground accelerations had occurred. These large swings could be attributed to the slack arising from the connection, as the loss of stiffness rendered the structure sensitive to smaller accelerations.

From the simulations, it was also observed that for a given target or design drift, a standard bracket could be replaced with a PFC of a substantially smaller capacity (ranging from half to two-thirds) to facilitate inelastic design. At the same time, the reduction in base-shears gained from using the optimized PFC (reduced capacity) ranged from 1.9 to 5.0. This shows that non-negligible reduction in base-shears are possible while keeping peak displacements at acceptable limits. If capacity design principles are adhered to (such that the connections fail before the members), then a lower connection capacity implies that cost savings are possible from reduced structural member sizes. In addition, further savings are possible with lower over-strength factors, since the 95th percentile failure load is more easily defined for pure embedment.

With the PFC, performance advantages can be gained in terms of reliable strength, consistent stiffness, smaller displacements and superior ductility when compared to the traditional design approach which utilizes numerous small-diameter fasteners. By preventing pinching in timber connections, it is shown that timber structures do not have to suffer from poor dynamic performance for the sake of a minimum amount of ductility.

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