Controlling Seismic Response using Passive Energy Dissipating Cladding Connections

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ABSTRACT: The basic function of passive energy dissipation (PED) devices is to absorb a portion of an earthquake's energy, thereby reducing the demand on structural members. In this way, such devices also limit the amount of damage to both the structure and its non-structural components in an earthquake. This paper examines the use of innovative cladding connections as suitable PED devices in multi-storey buildings. Use of such connections would also avoid the risk of brittle connection failures, like those observed during the Canterbury earthquake sequence.

Quasi-static, uni-directional cyclic testing was conducted at the University of Canterbury of a single-storey, single-bay reinforced concrete frame clad with precast concrete panels. The panels were attached to the frame using U-Shaped Flexural Plates as potential PED cladding connections. Such connections utilise the relative displacement between a structure and its cladding during an earthquake to dissipate energy. The connections produced stable hysteretic damping up to 3.5% interstorey drift. Analytical models of the cladding connections were developed and incorporated into 2D numerical models of various buildings. Response history analyses were conducted, examining the building response and the energy demands of various components, both with and without cladding. Results show that PED cladding connections can potentially halve the full hysteretic energy of a structure as well as reduce inter-storey deflections. By being easily designed for various levels of participation, PED cladding connections can potentially be applied to both new and retrofitted buildings.

1 INTRODUCTION

A building fully clad in precast concrete cladding presents an increase of approximately 20-30% in the inertial mass of multi-storey building (Pall, 1989). This increased mass means increased seismic forces during earthquake excitation. However, unlike other decorative type curtain walls, precast concrete cladding has inherent strength and stiffness that is typically ignored. Current design philosophies attempt to isolate cladding from interacting with the frame during deformations due to wind and earthquake loading (Arnold, 1990). Bolted connections with slotted or oversized holes are commonly used to isolate panels as well as accommodate erection tolerances. However, recent studies have outlined how even when attempts to isolate the cladding are made, precast concrete cladding can still substantially increase the overall stiffness of a structure (Baird, Palermo, & Pampanin, 2012; Hunt & Stojadinovic, 2010; McMullin, Wong, Choi, & Chan, 2004).

Instead of attempting to isolate the structure-panel interaction, it is proposed to instead take advantage of it to dissipate energy. By doing so, deformations of the main structure can be reduced, preventing damage in both structural and non-structural components. Controlling the cladding participation requires the development of an advanced connection that has high ductility and damping qualities that results in high energy dissipation without failure during moderate or strong earthquakes (Pinelli, Craig, Goodno, & Hsu, 1993). These connections must also be simple to design, highly robust and limit the forces transmitted into the panel. This paper explores the possibility of using U-shaped flexural plates (UFPs) as such an advanced cladding connection to passively dissipate seismic energy.

2 BACKGROUND

2.1 Cladding-structure Interaction

A number of studies in recent years have shown that this disregard of precast cladding to carry lateral load or to add lateral stiffness is not accurate (Goodno & Craig, 1989). Both experimental and numerical studies have been conducted which show how precast cladding provides additional strength and stiffness. Shown in Figure 1 (left) is the numerical push-over response of a ten-storey building with and without the inclusion of cladding. The fully clad building model has an increase of max base shear and initial stiffness of 41% and 47% respectively. Shown in Figure 1 (right) is a plot of the peak drifts of a 25 storey building model subjected to two different ground motions. It can be seen that the drift is reduced when the model includes the interaction of cladding.

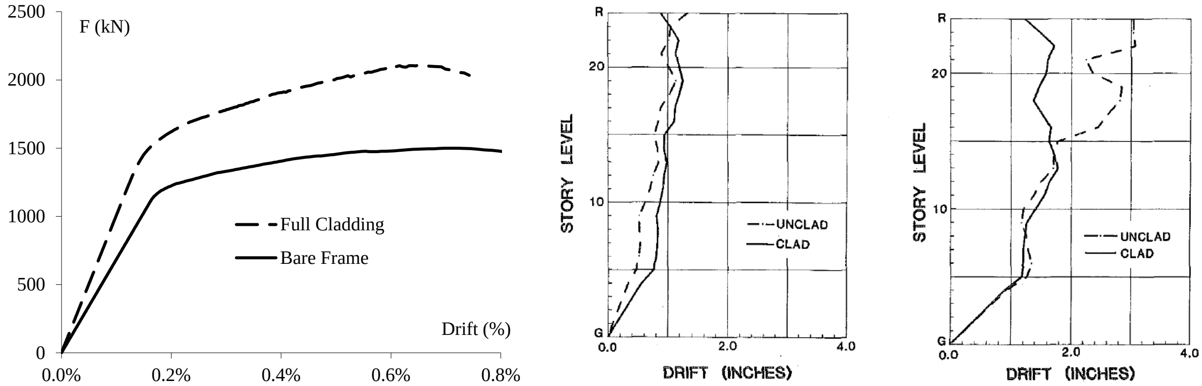

Figure 1: Pushover response of cladding systems compared to bare frame (left) (Baird et al., 2012); clad vs. unclad peak drift for 1940 El Centro and 1966 Parkfield ground motions (Goodno & Palsson, 1986)

By using cladding connections to passively dissipate earthquake energy, significant advantages can be achieved over conventional designs. The energy dissipation and damping can be distributed evenly over the height of the building and due to the increased damping, the overall response of the building is reduced and hence damage to non-structural elements and contents can be avoided (Goodno, 1983).

2.2 U-Shaped Flexural Plate Dissipators

U-Shaped flexural plates (UFPs) are formed by heating mild steel plates and bending a section around a fixed radius to form a U shape. Shown in Figure 2 (left) is the basic concept of a UFPs dissipation mechanism. UFPs have successfully been used in several structural dissipation applications, more recently as a device between coupled walls, like those shown in Figure 2 (right).

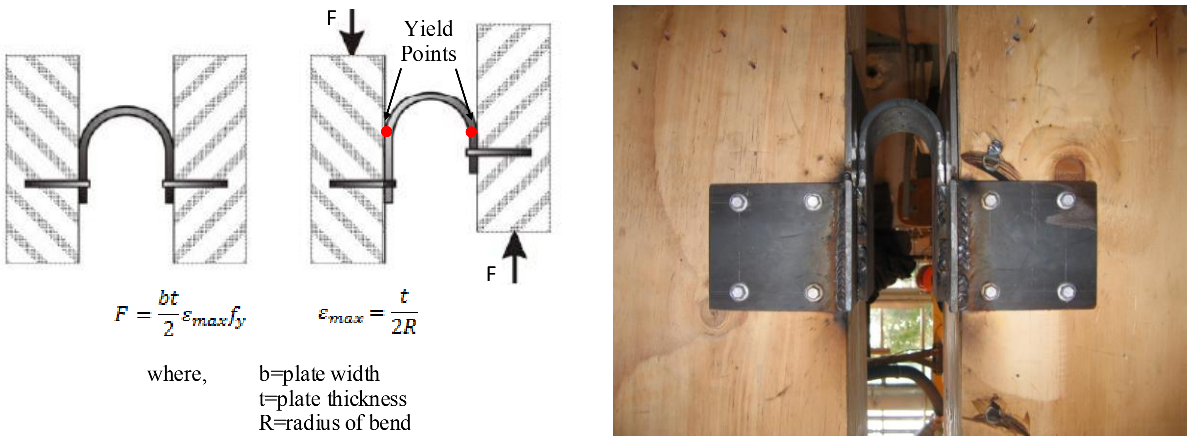

Figure 2: UFP dissipation mechanism (centre) and UFP device in between two timber shear walls (right)

UFPs were developed in 1972 by Kelly, Skinner, and Heine (1972) and are a form of flexural dissipator which utilise the post-yield ductility of steel to dissipate energy. When one side of the UFP is subjected to a displacement relative to the other side, the semi-circular section rolls along the plate and work is done at the two points where the radius of curvature is changed from straight to curved and vice versa. Thus the yielding point of the plate is moved back and forth along the plate.

UFPs can be designed for a large range of possible displacements and force levels by varying the plate thickness, width and radius. The design considers the displacement stroke such that the amount of steel that is deformed during loading is limited. This ensures the maximum strain is kept low enough to ensure that a specified lifetime is achieved.

3 EXPERIMENTAL TESTING

The UFPs tested had a width of 120 mm, thickness of 8 mm and curve radius of 60 mm. This gave an expected design force of 10 kN. This is similar to the maximum force that a traditional tie-back cladding connection would provide (Baird et al., 2012). The behaviour of the UFPs was established using quasi-static cyclic component testing. Full-scale testing of a structure-cladding subassembly was then performed utilising the UFPs as dissipative cladding connections.

3.1 Component Testing

A displacement controlled loading protocol was used to undertake the quasi-static, cyclic loading. The quasi-static loading regime consisted of three cycles at each displacement level. Two UFPs were tested in parallel in order for the loading to be symmetric. This was done to prevent a moment being applied to the loading apparatus and load cell. Shown in Figure 3 is the hysteretic loop for a single UFP. It can be seen that the UFPS produce a stable hysteretic loops with the maximum force in a single UFP is 12.5 kN. This is greater than the design force but is expected due to strain hardening in the steel. The overstrength factor of 1.25 is lower than that suggested by Kelly et al. (1972) who found that overstrength can be in the order of 1.45-2.15 greater than yield stress obtained from direct tension tests. The tests performed by Kelly et al. (1972) subjected the UFPs to high strokes relative to their radius. This resulted in high strains and large overstrength values and consequently a relatively low number of cycles to failure (between 20-150). The design of the UFPs as cladding connections aimed to minimise the strain in order for UFPs to be able to withstand a large number of cycles. Six strain gauges were attached to each UFP and the maximum strain recorded was approximately 2.0%.

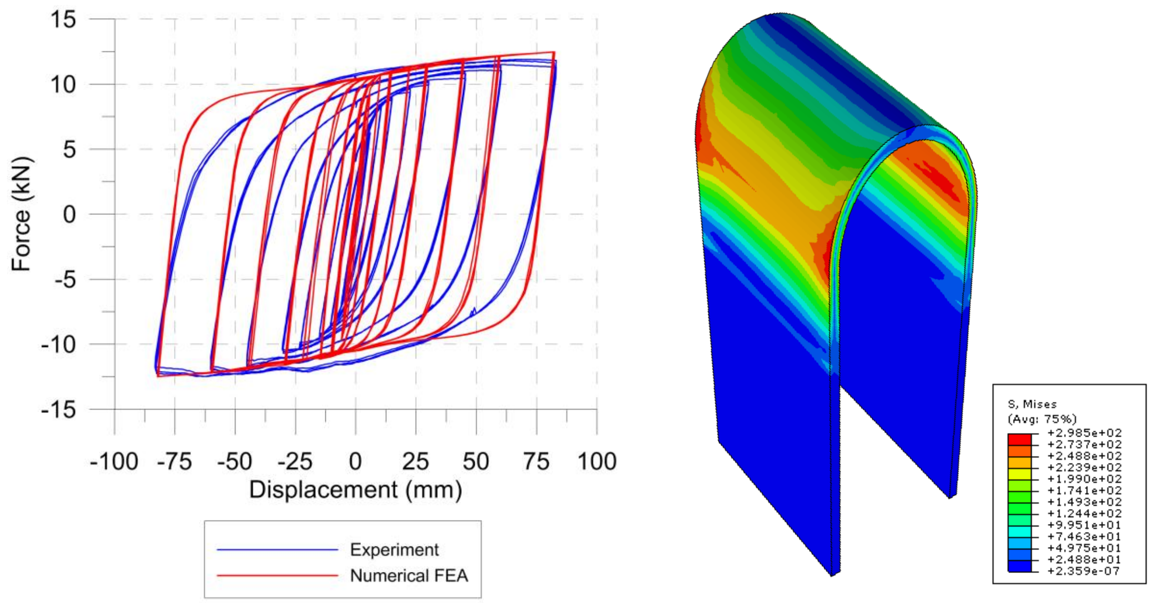

Figure 3: Experimental and numerical force-displacement behaviour of single UFP (left) and stress distribution of UFP during FEA showing location of yielding (right)

Finite element analyses (FEA) of the UFPs was also undertaken during the design phase. The force-displacement loop from the FEA can be seen overlaying the experimental data in Figure 3. The maximum force matches the experimental data well but the FEA did not accurately capture the Bauschinger effect in the steel. A snapshot of the stress distribution in the UFP during one of the FEA is also shown in Figure 3. It can be seen that the highest stresses occur where the plate transitions from flat to curved as expected.

3.2 Full-Scale System Testing

A full-scale, single-bay, single storey frame subassembly was constructed to test cladding systems at the University of Canterbury. The frame represents a portion of a reinforced concrete moment resisting frame. The beam and column members were individually cast and the beam-column connections utilise Precast Seismic Structural System (PRESSS) technology which allows the frame to be tested repeatedly to high drift levels with different claddings without sustaining significant structural damage (Priestley, Sritharan, Conley, & Pampanin, 1999). The frame is subjected to increasing levels of drift using a hydraulic jack attached to the top of the west column, as shown in Figure 4 (right). A quasi-static cyclic loading protocol is used in order to assess its seismic response (ACI - 374.1R, 2005).

A single precast concrete panel is the cladding tested as shown in the photograph in Figure 4 (right). The panel is 120 mm thick and 3.8 x 3.0 m in size, with a central opening of 2.0 x 1.6 m. The precast concrete panel is attached to the beams using two connection types: bearing connections and UFP connections, as show in Figure 4 (left). The bearing connections carry the gravity load of the panel back to the frame. These connections are metal angles securely bolted into place using anchors cast into the panel and frame and are located at the base of the panel. The bearing connection is not able to accommodate movement between the panel and frame as it is a fixed connection between the panel and the frame.

The UFP connections are located at the top of the panel. They must be able to resist out-of-plane forces due to wind and earthquake loading as well as be able to accommodate in-plane relative movement between the frame and the cladding panel during earthquake induced movement. It is the relative movement between the panel and frame which activates the UFPs and dissipates earthquake energy. Different configurations of UFP connections were tested and it was found that the connections were most stable when housed inside a steel hollow section, as shown in Figure 4 (left). The housing ensured uniform bending of the UFPs while also providing out-of-plane support and are similar to traditional slotted connections.

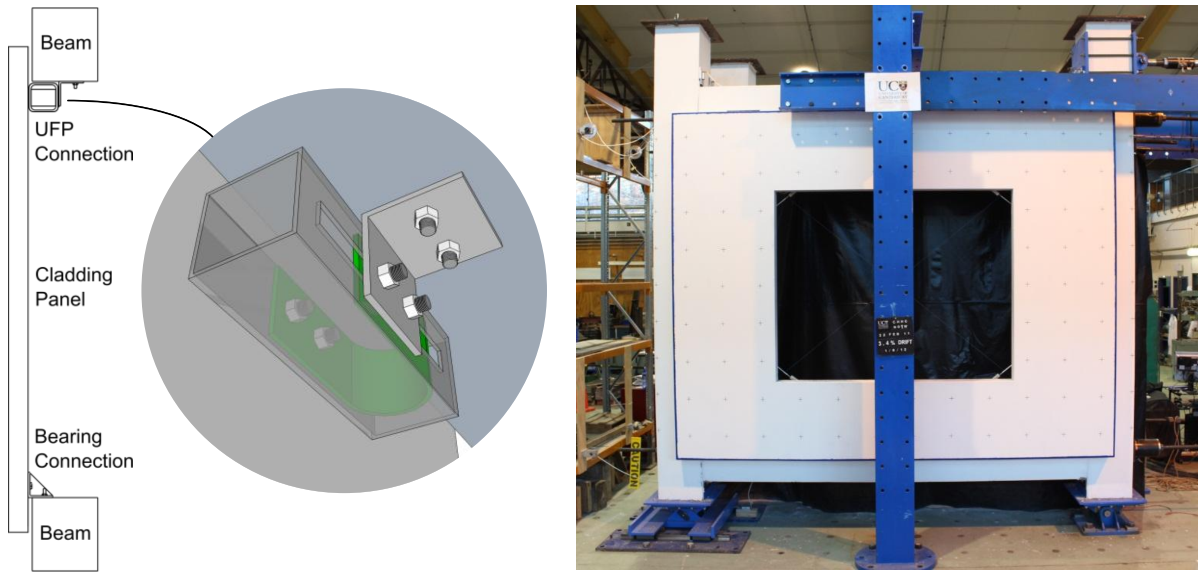

Figure 4: Cross section of cladding system with UFP connection (left) and photograph of test-setup (right)

Shown in Figure 5 is the force-displacement behaviour of the frame-cladding system when two UFP connections are used to connect the top of the panel to the frame. When the behaviour of the frame-cladding system is contrast with behaviour of the bare frame alone it can be seen that the UFP connections are increasing the strength and stiffness of the system while also creating increased hysteretic behaviour. There is no strength or stiffness degradation through the higher cycles to suggest damage is occurring in either the cladding panel or the frame. Inspection of the panel during testing confirmed that no cracking had occurred to the panel. The UFP connections did not show any signs of fatigue and retained their shape after being tested to large drifts, as can be seen in Figure 5 (right).

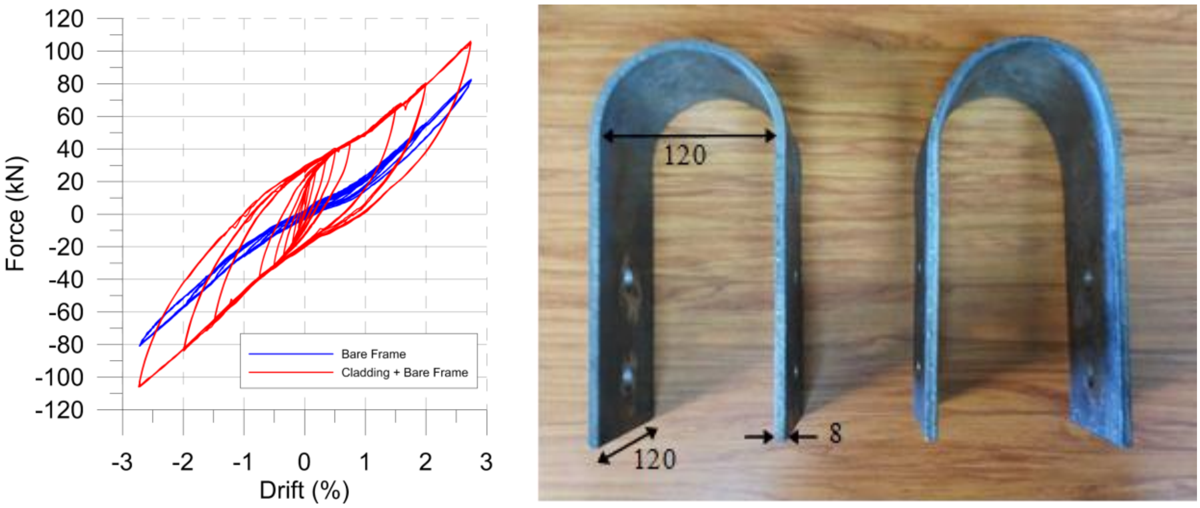

Figure 5: Force displacement behaviour of test frame with and without cladding using UFP connections (left), UFP connections before being tested (centre) and after being tested (right)

4 NUMERICAL MODEL

The numerical model used to examine the suitability of UFPs as passive energy dissipating cladding connections is based on the Red Book building (Bull & Brunsdon, 1998). This building acts as a design example of the New Zealand Concrete Code (NZS 3101, 2006). The building is designed for Christchurch prior to the increase in seismic hazard factor from 0.22 to 0.3 (DBH, 2011). Figure 6 (left) illustrates the plan view of the structure, with the seismic frame analysed highlighted. The bottom floor has a storey height of 4m while the upper floors have a storey height of 3.6 m. Design loads, forces and seismic masses were calculated according to New Zealand Design Standards

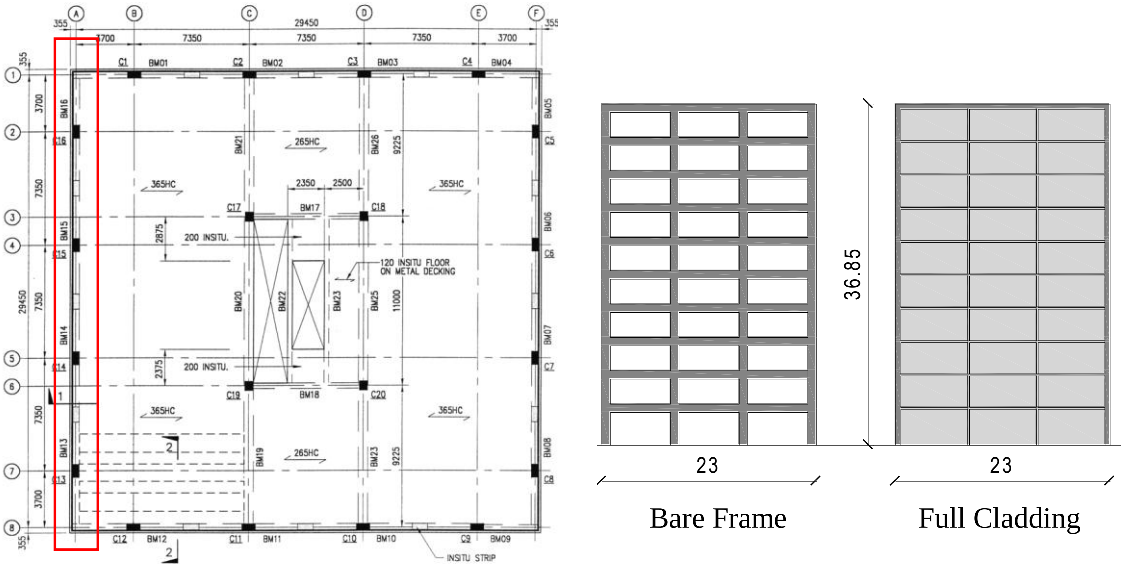

Figure 6: Plan view (left) and elevations (right) of the Red Book building with cladding

The building is modelled both fully clad and as a bare frame. A single precast concrete panel is located in every bay and spans one full floor height. The precast concrete panels are represented by elastic quadrilateral elements attached to the beams of the structure by bearings connections at the base and the UFP connections at the top.

5 TIME-HISTORY ANALYSIS

5.1 Earthquake Records

Time-history analyses have been performed investigating how the inclusion of passive energy dissipating cladding connections affects the seismic response of the building. A suite of fifteen recorded and properly scaled natural accelerograms have been used (Pampanin, Christopoulos, & Priestley, 2002). The records have been scaled according to NZS 1170.5 (2004), considering a seismic hazard factor of 0.3, soil type C, annual probability of exceedance of 1/1000 (R_s = 1.3) and a fundamental period of the structure equal to T_1=2.02 seconds (Bull & Brunsdon, 1998). Shown in Figure 7 are the 15 scaled records and the average of the scaled records compared to the New Zealand design spectrum.

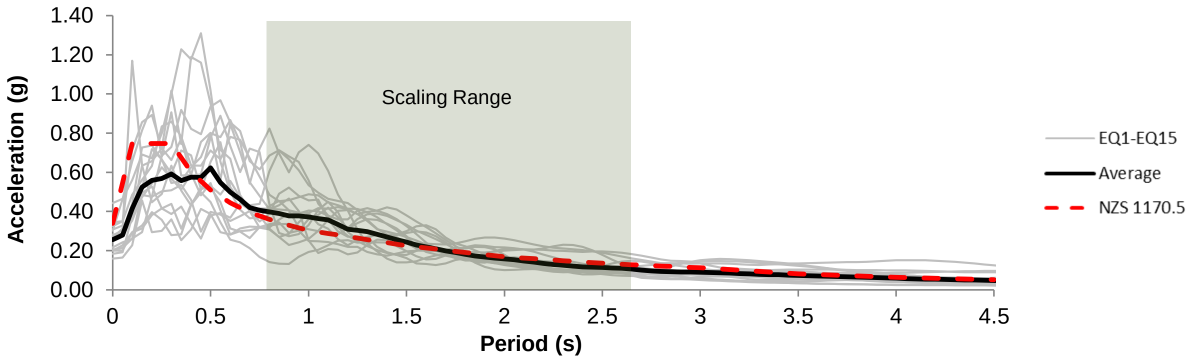

Figure 7: Scaled fifteen accelerograms and average compared with NZS 1170.5 design spectrum

5.2 Building Response

The maximum interstorey drift of the Red Book building to the fifteen earthquake records is shown below in Figure 8. The left figure shows the maximum drifts when the frame is modelled as a bare frame and the right figure shows the maximum drifts when the model includes cladding panels attached with UFP connections. The additional stiffness of the structure with the inclusion of cladding results in the mean interstorey drift reducing by 25%.

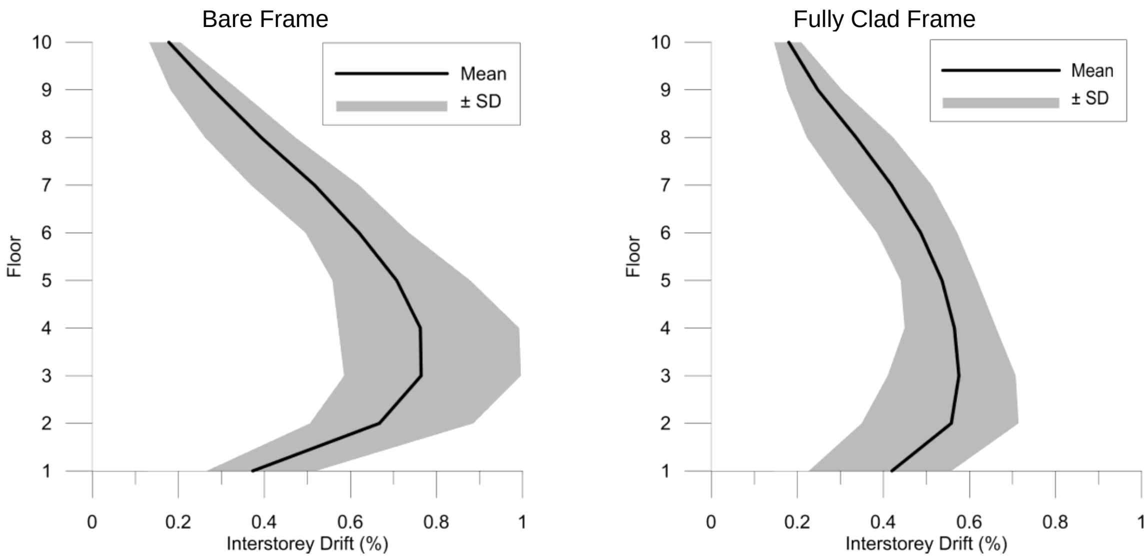

Figure 8: Drifts response of Red Book building when unclad (left) and fully clad (right)

5.3 Energy Analyses

The energy delivered to a structure by an earthquake must be consumed or stored within the structure. How the energy is consumed or stored can be broken down into the following energy forms: kinetic energy, elastic strain energy, viscous damped energy, and plastic strain energy (Soong & Dargush, 1997). The first two forms of energy can be considered as short term energy storage and the latter two forms as the main mechanisms that energy is dissipated. Energy dissipated through plastic strain energy in a building is a result of some sort of permanent damage, i.e. yielding or cracking. An energy based seismic design aims to reduce the plastic strain energy (or hysteretic energy) in the structure as much as possible as this reduces damage to the structure. In order to do this, energy must be dissipated by other means.

The top two plots in Figure 9 show the energy response of the Red Book building to the Superstition Hills (1987) earthquake record. It can be seen that the amount of viscous damped energy is nearly identical whether the building is clad or not. However, the amount of energy dissipated by damage to the structure drops 48%. It can be seen that some of this energy is instead consumed by the UFP devices. Because the building's stiffness is increased, the natural period is shortened. The effect this has depends greatly upon the earthquake ground motion, but in general, as can be seen in Figure 7, the shorter the period, the greater the acceleration and hence the more energy that is transferred into the structure. However, this is not always true, as can be seen for the Superstition Hills (1987) earthquake record, the total input energy decreases when the structure is fully clad.

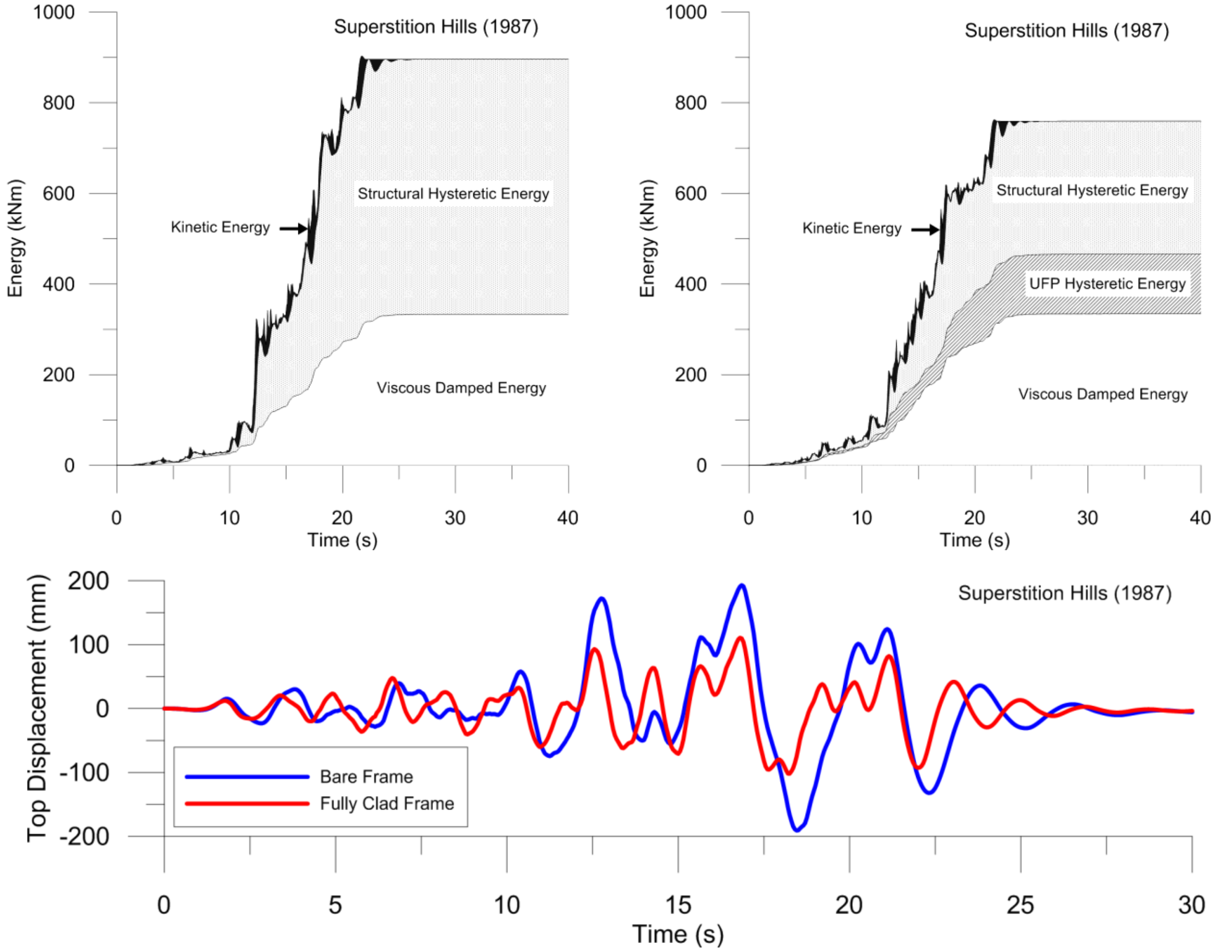

Figure 9: Energy response of Red Book building when unclad (top left) and fully clad (top right); horizontal displacement of top of structure when clad and unclad (bottom)

By tracking the horizontal displacement of the top of the structure during the earthquake record we can see in Figure 9 (bottom) how the UFP connections act to dampen the large displacements. The maximum displacement reached by the top of the structure is decreased by 42%.

6 CONCLUSIONS

The results of an experimental and numerical investigation into UFP cladding connections showed they have great potential as passive energy dissipation devices. By capitalising on the in-plane stiffness of precast concrete cladding panels, UFP connections dissipate earthquake energy that would otherwise result in damage to the structure. UFP cladding connections are also able to limit maximum displacements in a structure, reducing potential damage to other non-structural components. The design of passive cladding connections requires a trade-off between attracting more force since the structure is stiffened, and dissipating more energy. Numerical analyses found that even though the earthquake input energy on average increased when UFPs were used, the amount of hysteretic work done by the structure was always less than if the structure were treated as a bare frame.

7 REFERENCES

ACI - 374.1R. (2005). Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary: American Concrete Institute.

Arnold, C. (1990). Architectural Precast Cladding *Cladding Design: Recent Architectural Trends and Their Impact on Seismic Design* (pp. 29-30). Chicago, IL., USA.

Baird, A., Palermo, A., & Pampanin, S. (2012). *Understanding cladding damage: A numerical investigation into a Christchurch earthquake case study*. Paper presented at the 2012 New Zealand Society for Earthquake Engineering Conference, Christchurch, New Zealand.

Bull, D. K., & Brunsdon, D. (1998). *Examples of Concrete Structural Design to New Zealand Standards 3101*. Wellington, New Zealand: Cement & Concrete Association of New Zealand.

DBH. (2011). Building Controls Update No. 114: Immediate changes to sesimicity and foundation details for Christchurch Retrieved 10 January 2012, from http://www.dbh.govt.nz/

Goodno, B. J. (1983). *Cladding-structure interaction in highrise buildings*: Schools of Civil and Aerospace Engineering, Georgia Inst. of Technology, Atlanta.

Goodno, B. J., & Craig, J. I. (1989). *Historical Overview of Studies on the Contribution of Cladding to Lateral Resistance of Buildings*. Paper presented at the Architectural Precast Concrete Cladding - Its Contribution to Lateral Resistance of Buildings, Chicago, IL., USA.

Goodno, B. J., & Palsson, H. (1986). Analytical Studies of Building Cladding. *Journal of Structural Engineering, 112*(4), 665-676.

Hunt, J. P., & Stojadinovic, B. (2010). *Seismic Performance Assessment and Probabilistic Repair Cost Analysis of Precast Concrete Cladding Systems for Multistory Buildings*: Berkeley: Pacific Earthquake Engineering Research Center, University of California.

Kelly, J. M., Skinner, R. I., & Heine, A. J. (1972). Mechanisms of Energy Absorption in Special Devices for use in Earthquake Resistant Structures. *Bulletin of the New Zealand Society for Earthquake Engineering, 5*(3).

McMullin, K., Wong, Y., Choi, C., & Chan, K. (2004). *Seismic Performance States of Precast Concrete Cladding Connections*. Paper presented at the 13th World Conference on Earthquake Engineering Conference, Vancourver, B.C., Canada.

NZS 1170.5. (2004). Structural Design Actions, Part 5: Earthquake Actions - New Zealand. Wellington: Standards New Zealand.

NZS 3101. (2006). Concrete Structure Standard - Part 1. Wellington: Standards New Zealand.

Pall, A. S. (1989). *Friction Damped Connections for Precast Concrete Cladding*. Paper presented at the Architectural Precast Concrete Cladding - Its Contribution to Lateral Resistance of Buildings, Chicago, IL., USA.

Pampanin, S., Christopoulos, C., & Priestley, M. J. N. (2002). *Residual deformations in the performance-based seismic assessment of frame structures*. Pavia, Italy: IUSS Press.

Pinelli, J. P., Craig, J. I., Goodno, B. J., & Hsu, C. C. (1993). Passive control of building response using energy dissipating cladding connections. *Earthquake Spectra, 9*(3), 529-546.

Priestley, M. J. N., Sritharan, S., Conley, J., & Pampanin, S. (1999). Preliminary Results and Conclusions from the PRESSS Five-Story Precast Concrete Test Building. *PCI Journal*

Soong, T. T., & Dargush, G. F. (1997). *Passive Energy Dissipation Systems in Structural Engineering*. New York, USA: Wiley.