DESIGN OF A SHEAR CONNECTOR FOR A NEW SELF-CENTERING WALL SYSTEM

R.S. Henry[1], S. Aaleti[2], S. Sritharan[3] and J.M. Ingham[4]

[1] *Ph.D Candidate, Dept. of Civil and Environmental Engineering, University of Auckland*
Email: rhen048@ec.auckland.ac.nz
[2] *Ph.D Candidate, Dept. of Civil, Construction and Environmental Engineering, Iowa State University.*
[3] *Associate Professor and Assistant Chair, Dept. of Civil, Construction and Environmental Engineering, Iowa State University.*
[4] *Associate Professor and Deputy Head, Dept. of Civil and Environmental Engineering, University of Auckland.*

ABSTRACT :

Self-centering precast concrete walls have been found to provide excellent seismic resistance. Such systems, however, typically exhibit low energy dissipation, requiring supplementary dissipating components to improve their seismic performance. An economical option is to use mild steel shear connectors as energy dissipating elements. The design of steel shear connectors for a new precast wall system was undertaken using finite element analyses. Of the different types studies, an oval shaped connector (or O-Connector) was found to provide the most suitable response, with stable force-displacement behavior and large displacement capacity. An experimental test program was conducted to verify the performance of two different O-Connector designs, confirming the expected excellent response with sufficient energy dissipation. The experimental data demonstrated excellent correlation with the finite element model developed. The O-Connector has since been incorporated into a large scale PreWEC test specimen, behaving as expected and providing an excellent connector for the system.

KEYWORDS: Precast, concrete, wall, self-centering, connector, finite element

1 INTRODUCTION

Self-centering structural systems that typically use unbonded post-tensioning can provide excellent seismic resistance, enabling them to undergo large lateral deformations while minimizing damage. However, due to their elastically dominated response such structures generally exhibit low energy dissipation, often requiring supplementary energy dissipating devices to improve their seismic performance.

The use of precast concrete walls as self-centering components was studied extensively during the PREcast Seismic Structural Systems (PRESSS) research program (Priestley 1991). During the research program a jointed wall system using unbonded post-tensioning was developed and incorporated into the five storey test building (Nakaki et al. 1999; Priestley et al. 1999). The jointed wall system uses two of more precast concrete walls, post-tensioned to the foundation using unbonded tendons, and connected along the vertical joints with special energy dissipating shear connectors. As part of the PRESSS program, an experimental study into behaviour of various shear connectors was conducted under a reverse cyclic vertical displacement history (Shultz and Magana 1996). A U-shaped flexural plate (UFP) was found by Shultz et al. to be the most suitable connector, and subsequently included in the jointed wall system of the PRESSS test building (Priestley et al. 1999). Because it was constructed from stainless steel, the drawbacks of the UFP connectors are that it is expensive and its behavior becomes dependent on strain history due to its isotropic hardening.

2 PREWEC WALL SYSTEM

While the PRESSS jointed wall system performed well during large scale testing, its implementation into real structures has been limited. This can be attributed to a reduction in moment resisting capacity when compared with a similar monolithic reinforced concrete wall, reducing its cost-effectiveness. To rectify this deficiency, a new system consisting of a Precast Wall with two steel or concrete End Columns (or PreWEC) has been developed (Aaleti and Sritharan 2007). All components are anchored to the foundation using unbonded post-tensioning and the special shear connectors are placed along the vertical joints to link the wall and column together horizontally. Similar to the jointed wall system, under lateral loads, the PreWEC system largely concentrates inelastic deformations at a single crack that opens up at the base of the wall and columns. The post-tensioning is unbonded to reduce the strain demand and designed to remain in the elastic range up to the design level drift, providing a restoring force to self-center the structure. Through this innovative arrangement of components, the PreWEC system can be designed to attain a moment capacity equal to that of a comparable monolithic reinforced concrete wall, which was not possible with the jointed wall system concept.

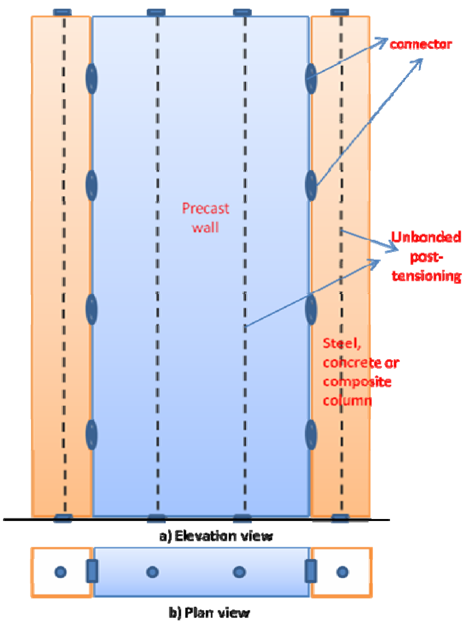


Figure 1: PreWEC system concept

3 CONNECTOR DESIGN

3.1 Connector Requirements

The shear connectors in the PreWEC system have two functions. Firstly, they transfer forces between the wall and column elements, adding to the lateral force resistance. Secondly, they act as the primary source of energy dissipation in the system. Under cyclic loading, the connectors are subjected to relative vertical displacements at the wall to column interface. The relative vertical displacements are much larger in one direction due to differences in the levels of uplift that occur at the wall and column toes. This leads to the connectors experiencing an unsymmetrical cyclic displacement history.

A design target force-displacement envelope was developed for the connector based on the analysis of a six story PreWEC wall specimen (Aaleti and Sritharan 2007). The connector was required to maintain a stable force-displacement response, maximize energy dissipation, and be able to sustain relative vertical displacements of up to 60 mm with the peak strains generated limited to less than 0.1. This value was chosen to reflect a dependable strain limit for mild steel, preventing fracture when subjected to repeated large amplitude cyclic deformations.

3.2 Types of connector

After examining the results from the experimental investigation by Shultz and Magana (1996), connectors using direct shear or tension/compression mechanisms were deemed less suitable. While these connectors can perform well, they tend to generate large strain demands, resulting in displacement capacities much less than the 60 mm requirement selected for the PreWEC system.

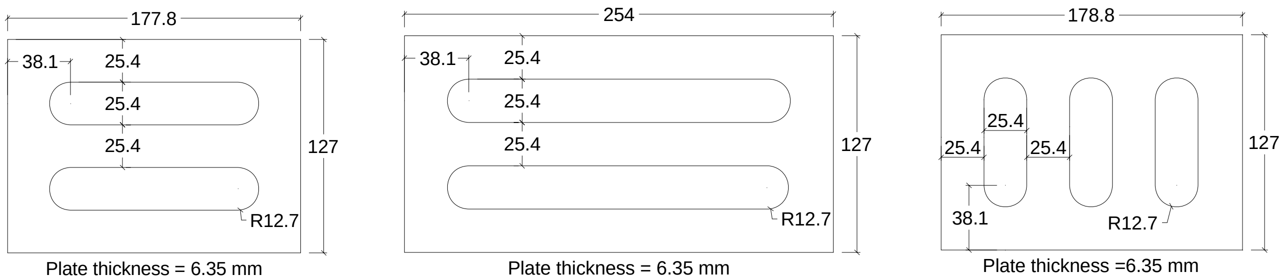
In consideration of the above finding, flexural yielding was identified as the most desirable mechanism for a PreWEC connector. More indirect load paths lower the strain demand, resulting in a larger displacement capacity. To develop an economical connector the use of grade A50 mild steel was preferred. For this reason the U-shaped flexural plate (UFP) was ignored as it required the use of stainless steel.

3.3 Finite Element Modeling

A series of finite element analyses were conducted to investigate the performance of different connector types. These finite element models (FEMs) are detailed by Henry et. al (2008). A summary of the analysis results and conclusions are included herein. All plate connectors modelled were assumed to be manufactured using grade A50 mild steel plate.

3.3.1 Slotted Flexural Plate (SFP)

The first connectors modelled were a series of slotted flexural plates (SFP), shown in Figure 2. The FEM predicted a good response for SFP-1 with a strength just 10% below the design strength. However, the strain demand was very high resulting in a predicted displacement capacity of only 11 mm, 82% below the required capacity. The aspect ratio was increased for SFP-2 by lengthening the plate. The increased aspect ratio promoted a more flexure dominant response, reducing the strain demand and increasing the displacement capacity to 26 mm. The predicted strength of SFP-2 was, however, about 50% lower. The third connector, SFP-3, had vertically orientated slots instead of the horizontal slots. This increased the location for plastic action resulting in a predicted strength of about 60% over the design target. The displacement capacity of SFP-3 was just 8 mm, only 13% of the required capacity of 60 mm. While the SFP connectors provide a promising connector with a stable response and good energy dissipation from the flexural yielding mechanism, they are better suited for applications with lower displacement demands.

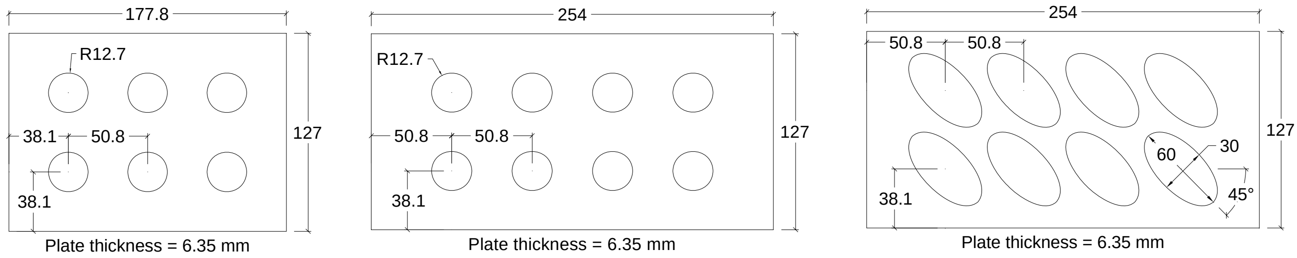


(a) SFP-1 (b) SFP-2 (c) SFP-3

Figure 2: Dimensions of different slotted flexural plate (SFP) connectors

3.3.2 Flexural Plates with Holes

A variation of the SFP was trialed, replacing the slots with a series of holes. This configuration increased the number of locations where plastic deformations can occur, resulting in increased strengths and energy dissipation. Three different flexural plates with holes were modelled and the details are shown in Figure 3. H1 had similar plate dimensions to SFP-1, with the slots replaced with six holes. The FEM predicted an increased strength of three times the required capacity. The strain demand was still very high limiting the displacement capacity to just 11 mm. Again the aspect ratio of the connector was increased to increase its displacement capacity, producing connector H-2. This successfully reduced the strain demand resulting in an increased displacement capacity of 21 mm. An innovative configuration was tried for H-3, using elliptical holes inclined at 45 degrees. This hole pattern decreases the strain demand in the positive loading direction allowing a more dominant flexural mechanism as the holes open up. Connector H-3 successfully increased the displacement capacity to 25 mm, in doing so the connector strength was significantly reduced to 1.4 times of the design target. The flexural plates with holes showed a considerable increase in strength, but the displacement capacities are still less than half the required 60 mm for the PreWEC system.

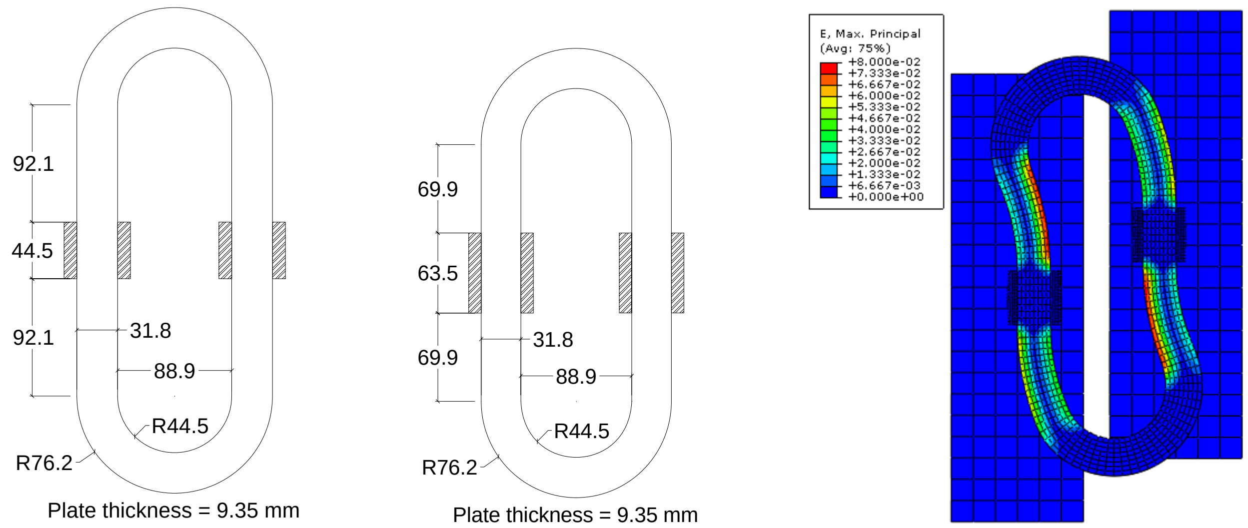


(a) H-1 (b) H-2 (c) H-3

Figure 3: Dimensions of different slotted flexural plates with holes

3.3.3 Oval-Shaped Flexural Plate (O-Connector)

To increase the displacement capacity, an oval-shaped flexural plate connector was designed. Consisting of an oval shaped loop cut from a steel plate and welded over a small section at the center of each leg, the O-connector was developed into the two designs shown in Figure 4a and 4b. With no direct tension path the plastic deformation in the O-connector occurs as an almost pure flexural mechanism in the legs, significantly reducing the strain demand. The preliminary FEM predicted strengths of about 85-90% of that required, and displacement capacities in excess of 60 mm. A plot of the FEM showing the peak principal strains at the 60 mm vertical displacement is shown in Figure 4c. The flexural mechanism is clearly visible in the connector legs.



(a) O-1 (b) O-2 (c) FEM

Figure 4: Dimensions of O-shaped flexural plate connectors and FEM output

3.3.4 Summary of FEM analyses

The FEM analysis results are summarised in Table 1. The results indicate that the flexural plates with slots or holes can provide excellent connectors when the displacement requirements are small; however, they are not suitable for the PreWEC system designed for high seismic regions. These connectors may be more suitable for applications with lower displacement demands such as between precast floor units or wall to floor connections. It was concluded from the FEM study that the most suitable connector was the O-Connector, which provided both the adequate strength and desirable displacement capacity.

Table 1: Summary of connector dimensions and capacities obtained from FEMs

Connector	Length (mm)	Thickness (mm)	Openings	Strength		Displacement capacity	
				kN	% Required Capacity	mm	% Required Capacity
SFP-1	177.8	6.35	Horizontal slots	32	91	11	18
SFP-2	254	6.35	Horizontal slots	16	46	26	43
SFP-3	177.8	6.35	Vertical slots	56	160	8	13
H-1	177.8	6.35	Holes	108	309	13	22
H-2	254	6.35	Holes	86	246	21	35
H-3	254	6.35	Elliptical holes	50	143	25	42
O-1	N/A	9.53	N/A	30	86	60+	100
O-2	N/A	9.53	N/A	31	89	60	100

4 EXPERIMENTAL VALIDATION

To validate the FEM predictions and to confirm the expected performance five tests were performed on the O-Connector. Connector O-1, shown in Figure 4a, was used during tests A1 & A2 while O-2, shown in Figure 4b, was used for tests B1, B2 & B3. In each test, four individual connectors were tested to maintain symmetry of the test setup. The connectors were cut from 9.53 mm thick grade A50 steel plates using a laser cutting technique to reduce the residual stresses induced during the fabrication process.

4.1 Test setup

A test setup, visible in Figure 5a, was designed using steel tubes and steel plates to apply the desired vertical loading to the O-Connectors. In order to eliminate any eccentric loading, four O-Connectors were welded between a U-frame and H-section and tested simultaneously. Loading was applied in a displacement control mode, with a relative vertical displacement applied to the O-Connectors.

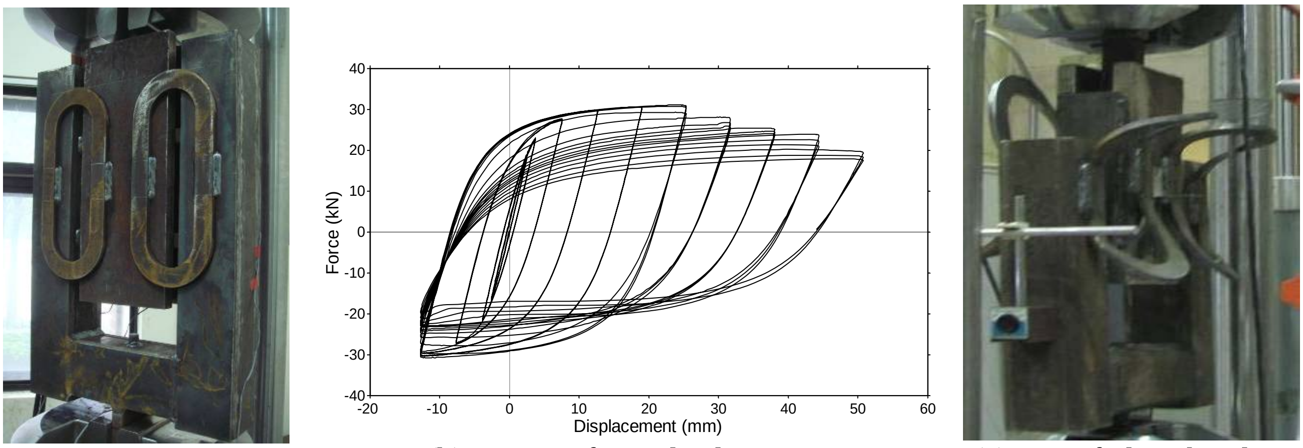
The loading protocol used was developed to simulate the expected displacement history to which the connectors will be subjected during a reverse cyclic load test of a PreWEC prototype specimen (Aaleti and Sritharan 2007). The displacement history consisted of an unsymmetrical reverse cyclic loading up to a maximum peak displacement of 50.8 mm in the positive direction. As explained previously, the loading of the connectors in the PreWEC system is unsymmetrical, so displacements in the negative direction were capped at 12.7 mm. At each displacement level, the connectors were cycled three times to observe the stability of the force-displacement response. During Test A2, the loading protocol was modified and the connectors were subjected to a true displacement history measured during the large scale testing of the PreWEC-1 specimen (Sritharan et al. 2008). The recorded displacement history ended at a peak positive displacement of 53 mm, so the record was extrapolated to a peak of 71 mm until failure occurred to the connectors.

4.2 Experimental Results

4.2.1 Test A1 and A2

The results from Test A1 indicated that the O-connectors generally behaved as expected. It can be seen in the force-displacement response in Figure 5b that the connectors provided strong stable hysteresis loops with sufficient energy dissipation. However, the O-Connectors began to experience out-of-plane buckling during the 31.75 mm displacement cycle (see Figure 5c). This caused significant strength degradation during larger displacement cycles. To prevent this out of plane movement occurring in the future tests, a retrofit to the connector was provided with a pair of steel restraining plates, which can be seen in Figure 7 that shows Test B3.

The results from Test A2 showed improved performance with no out-of-plane buckling occurring. The force-displacement loops, shown in Figure 6a, were stable up to positive displacements of 57 mm, with some strength degradation occurring during the cycle to 71 mm when the connectors started to fracture.



(a) Test setup (b) Test-A1 force-displacement (c) Out-of plane bending

Figure 5: Test-A1

A FEA results obtained for Test A2, detailed in Henry et al. (2008), are included in Figure 6a. It is observed that the FEM provides excellent comparison to the measured response of the connectors. The FEM also adequately captured the loading and unloading stiffness while marginally underestimating the strength. Additionally, the FEM predicted a displacements capacity of 62.5 mm for O-1 at the 0.1 strain limit. The Test-A2 connectors remained intact during cycles to 57 mm, starting to fracture during the 71 mm cycle, indicating that the displacement capacity established by the FEM was fairly accurate.

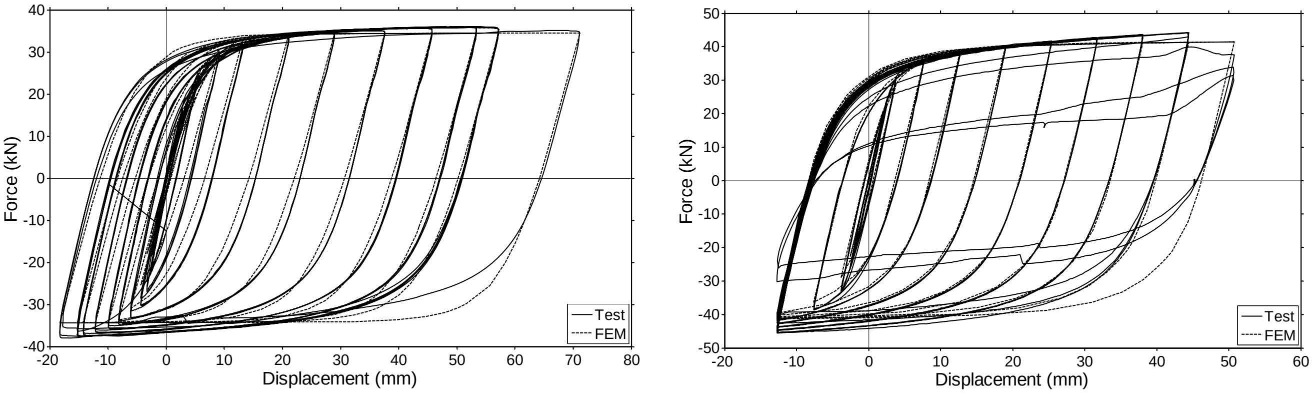


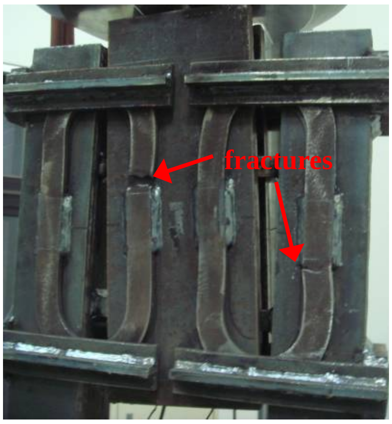
Figure 6: Force-displacement responses obtained for (a) Test A2 and (b) Test B3

4.2.2 Test B1, B2 and B3

Three tests were completed on connector O-2. Test B1 did not include the out-of plane restraint and showed similar behavior to Test-A1 with out-of-plane buckling occurring during the 31.75 mm cycles and significant strength degradation. Tests B2 and B3 both included the restraints and provided almost identical results. The force-displacement response of B3 is plotted in Figure 6b. The setup used during Test B3, the displaced shape of an O-2 connector and the final failure mode are shown in Figure 7. The Test-B connectors showed a 25% increase in strength compared to those from Test-A, and also a reduced displacement capacity with fractures first appearing during repeated cycles at 44.45 mm. This change in response is primarily due to the difference in dimensions between O-1, used in Test A, and O-2, used in Test B. The shorter leg length of O-2 is believed to have caused larger plastic rotations in Test B connectors, increasing the strains and thereby strength of the connectors. Secondly, the steel used in Test A was sourced in the US and Test B sourced in Taiwan. Material tests found that the later steel to be of higher strength, contributing to the observed behaviour of the connectors in Test B. The FEM run for Test B3, including this new steel stress-strain definition, is plotted in Figure 6b, showing accurate prediction of the connector's behaviour with again a slight underestimation of the strength.

(a) Test setup

(b) At 32 mm displacement

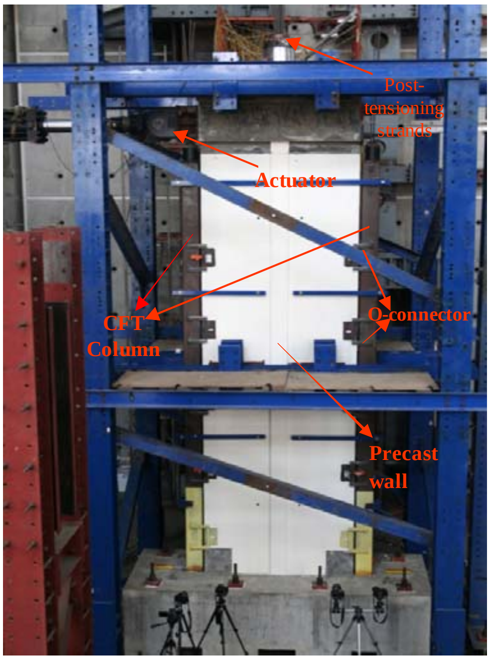


(c) Fractured O-Connectors

Figure 7: Photos from Test B3

5 LARGE SCALE-PREWEC TEST

Following the success of the O-Connector experimental validation, the O-2 design was included in a large scale testing of a PreWEC specimen detailed in Sritharan et al. (2008). A total of 20 connectors were used on the 6 m tall wall system shown in Figure 8a. The connectors were welded to the end column on one side and to a steel plate embedded in the precast concrete wall on the other. The connectors behaved as expected providing sufficient shear transfer and energy dissipation during the reverse cyclic testing. The structural condition of the O-connector at a 3% drift is shown in Figure 8b, which clearly shows the flexural mechanism experienced by the legs of the connectors. Failure of the O-connectors occurred as multiple fractures started to occur during cycles to ±3% wall drift. This was the expected failure point based on the previous component testing and well in excess of the design level drift of 2%. Interestingly, even after many of the connectors' legs were completely ruptured they continued to transfer forces when they closed up. As a result the wall showed no significant strength degradation when cycled to 3.5%.



(a) PreWEC test setup

(b) O-Connector at 3% wall drift

Figure 8: Large-scale test of a PreWEC specimen

6 CONCLUSIONS

The design of steel shear connectors for use in the recently developed PreWEC self-centering precast concrete wall system was completed. A series of finite element analyses led to the design of an oval-shaped connector. This connector provided excellent hysteretic response with sufficient energy dissipation and a large displacement capacity. While the O-Connector was selected as the most suitable connector type for PreWEC systems in high seismic regions, other connectors developed examined in this investigation may be used in situations that require lower displacement demands.

An experimental program was conducted that included five different tests with each test examining the performance of four O-connectors simultaneously. The experimental results validated the connector's performance, demonstrating excellent force-displacement characteristics with stable hysteresis loops and sufficient energy dissipation. The experimental results also provided validation to the analysis of the FEM, which was found to provide excellent prediction of the O-connector's response.

The successful design of the O-connector was included in a PreWEC test specimen. The connector behaved as expected, providing a stable and reliable response with sufficient energy dissipation provided to the system. The test confirmed the suitability of the O-connector for such self-centering wall systems.

ACKNOWLEDGMENTS

The study presented in this paper was undertaken as part of the International Research and Education in Engineering (IREE) program of the National Science Foundation (NSF) as a supplement to Grant No. CMS 0324559. The program directors administered the IREE funding at NSF were Drs. Win Aung and Douglas Foutch. Any opinions, findings, and conclusions expressed in this paper are those of the authors, and do not necessarily reflect the view of NSF. The authors also like to acknowledge the National Center for Research on Earthquake Engineering (NCREE) in Taiwan, particularly Professor Keh-Chyuan Tsai and Dr. Kuang-Yen Liu, for their assistance in the completion of the Phase B connector tests as well as the large scale PreWEC test.

REFERENCES

Aaleti, S., and Sritharan, S. (2007). "A precast wall with end columns (PreWEC) for seismic applications." *Proc., 8th Pacific Conference on Earthquake Engineering*, Singapore, Paper 157.

Henry, R. S., Aaleti, S., Sritharan, S., and Ingham, J. M. (2008). "Concept and finite element modeling of new steel shear connectors for self-centering wall systems." *Submitted to: ASCE Journal of Engineering Mechanics*.

Nakaki, S. D., Stanton, J. F., and Sritharan, S. (1999). "An overview of the PRESSS five-story precast test building." *PCI Journal*, 44(2), 26-39.

Priestley, M. J. N. (1991). "Overview of PRESSS research program." *PCI Journal*, 36(4), 50-57.

Priestley, M. J. N., Sritharan, S., Conley, J. R., and Pampanin, S. (1999). "Preliminary results and conclusions from the PRESSS five-story precast concrete test building." *PCI Journal*, 44(6), 42-67.

Shultz, A. E., and Magana, R. A. (1996). "Seismic behavior of connections in precast concrete walls." *Proc., Mete A. Sozen Symposium, ACI SP 162*, American Concrete Institute, Farmington Hills, MI.

Sritharan, S., Aaleti, S., Henry, R. S., Liu, K. C., and Tsai, K. C. (2008). "Introduction to PreWEC and key results of a proof of concept test." *Proc., Nigel Priestley Symposium*, Kings Beach, CA.