SEISMIC PERFORMANCE OF FLAT-SLAB SHEAR REINFORCEMENT

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SUMMARY

The intent of this research program was to study the response of slab-column connections containing various types of shear reinforcement when subjected to combined gravity and cyclic lateral loading. The four test specimens were a half-scale representation of interior slab-column connections in a prototype flat plate building. All test specimens were identical except for the type of shear reinforcement used in the slab. The control specimen had no shear reinforcement, while the other specimens had closed hoop stirrups (open hoop with closure clip), single leg stirrups, and headed studs as shear reinforcement.

All test specimens were able to withstand lateral drifts in excess of 3 percent prior to significant deterioration of the slab concrete around the slab-column connection. The control specimen failed as a result of punching shear failure around the slab-column connection during the 3.5 percent drift cycle. None of the specimens with slab shear reinforcement experienced punching failure during testing to 8 percent lateral drift.

All three types of slab shear reinforcement proved equally effective in resisting punching shear failure and significantly increasing the lateral load ductility of the slab-column connection. The simplicity of placement of the headed stud reinforcement makes it an attractive alternative to the single leg stirrups and the closed hoop stirrups.

INTRODUCTION

Flat slab building systems are utilized extensively for construction of apartments, hotels and office buildings. Flat slab construction is common throughout the USA and indeed much of the World. In Hawaii, the large visitor and tourist trade has resulted in the construction of a large number of hotels and rental apartment buildings. The majority of these low to mid-rise buildings utilize flat slab construction. The advantages of a flat-slab floor system are numerous. The simplicity of formwork and resulting speed of construction make for a short and economical construction period. Low floor to floor heights (generally 3 meters or less) reduce the total building height thus reducing lateral loads, cost of building cladding, cost of vertical mechanical and electrical lines, and air-conditioning/heating costs.

The economy of this type of construction is further enhanced by utilizing the simplest form of flat slab, namely a flat plate system with no variations in slab depth. A critical design criterion for flat plates is the punching shear strength of the slab at the slab-column connections. To avoid adding drop panels or beams to increase the shear capacity of the slab, various types of shear reinforcement can be used in the slab around the connection.

The research program reported here involved the fabrication and testing of four large-scale flat-plate interior slab-column connections with some of these common types of slab shear reinforcement. The specimens were tested under combined gravity and cyclic lateral load.

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TESTING PROGRAM

Test Specimens

This research program consisted of testing four slab-column connections. Each specimen was a half-scale representation of an interior connection in a prototype flat plate building (Fig. 1). All test specimens were identical except for the type of shear reinforcement used in the slab. Three types of shear reinforcement were considered as shown in Figure 2 below.

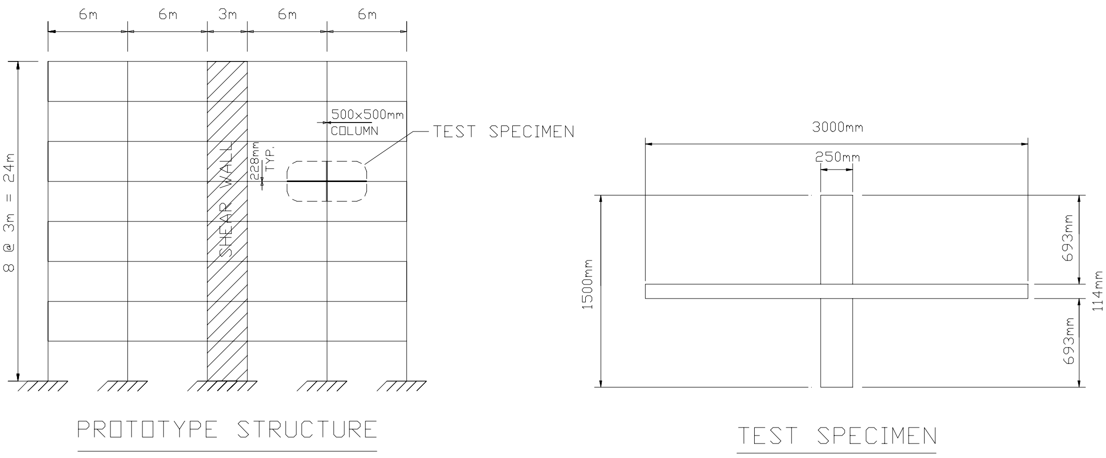
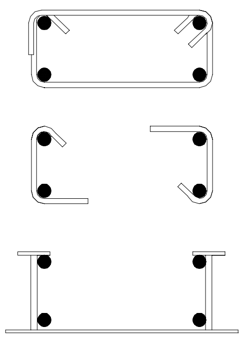


Figure 1: Prototype structure and test specimen



Specimen 1C - No shear reinforcement (Control)

Specimen 2CS - Closed hoop stirrups
(Open hoop with closure clip)

Specimen 3SL - Single leg stirrups

Specimen 4HS - Headed stud shear reinforcement

Figure 2: Slab shear reinforcement used in the test specimens

The slab reinforcement in specimens 2CS and 4HS is shown in Figures 3 and 4 respectively.

Figure 3: Closed hoop stirrups – Spec. 2CS

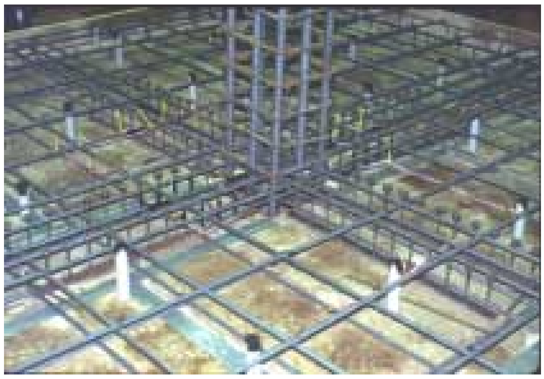


Figure 4: Headed studs – Spec. 4HS

Test Displacement Routine

The specimens were subjected to an incrementally increasing cyclic displacement routine (Fig. 5). The intent of this displacement routine was to study the connection behavior under increasing levels of lateral drift and to determine the failure drift level for a connection using a particular type of shear reinforcement. In addition, repeated cycles of the same magnitude and repeated 1 percent drift cycles allowed a study of the stiffness degradation in the specimens. Phase I of the test routine involved cyclic displacements up to 5 percent drift in each direction. At 5 percent drift, the test frame actuator had reached its maximum stroke. The actuator was repositioned so as to continue the test as Phase II with loading only in one direction up to a maximum of 8 percent drift.

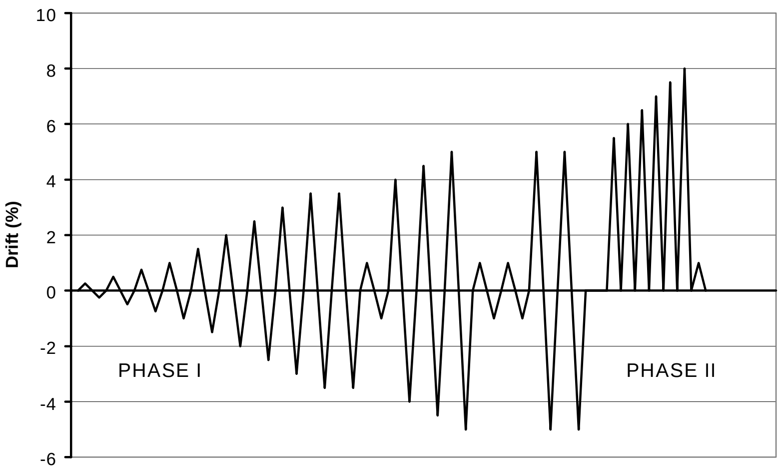


Figure 5: Lateral displacement routine

Test Setup

The specimens were tested as shown in Figure 6. The base of the column was attached to the laboratory strong floor by a pinned connection. Concrete weights suspended from the slab applied a constant vertical load to simulate sustained dead and live loads on the slab. The slab edges were supported from the floor below by instrumented load rods to allow rotation and lateral movement but no vertical movement. The top of the column was attached to a horizontal actuator, which applied the prescribed lateral displacement routine.

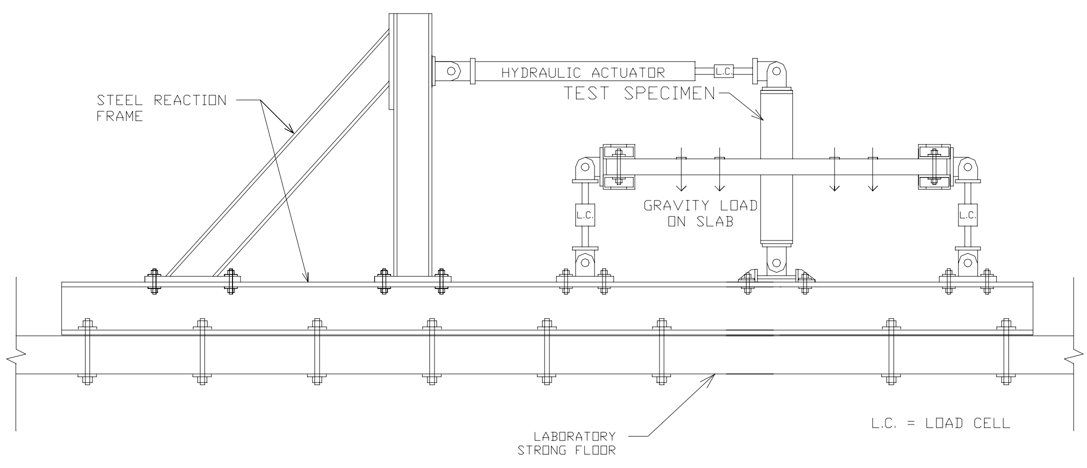


Figure 6: Test setup

Instrumentation

Load cells were used to determine reactions so that all column and slab bending moments and shears were known. Horizontal displacement was monitored at the top and bottom of the column. Strain gages were placed on the vertical and horizontal legs of the shear reinforcement and on certain slab longitudinal bars to determine the stresses in the reinforcement. Crack patterns were recorded at each drift level during the tests.

The experimental work was performed in the Structures Testing Laboratory at the University of Hawaii. This 300 square meter laboratory is equipped with a 115 square meter strong floor. The laboratory is equipped with a hydraulic pump and servo-controlled MTS hydraulic actuators. An MTS TestStar II Digital Controller was used to perform the displacement controlled testing. A National Instruments Data Acquisition system connected to a Personal Computer recorded all instrumentation readings.

TEST RESULTS

Cracking Behavior

During the application of gravity load on the slabs, flexural cracks developed at the face of the column in all specimens. With the application of lateral load, additional flexural cracks formed across the entire width of the slab. In addition, diagonal torsional cracks appeared adjacent to the side faces of the column. The typical crack pattern at 1.5 percent drift for all specimens is shown in Figure 7. During the 3.5 percent drift cycle for specimen 1C, a punching shear crack formed without warning. Figure 8 shows the projection of the shear crack on the top surface of the slab. None of the specimens with slab shear reinforcement experienced shear failure even at drift levels of 8 percent (Figs. 9 and 10).

Figure 7: Typical cracking at 1.5% drift.

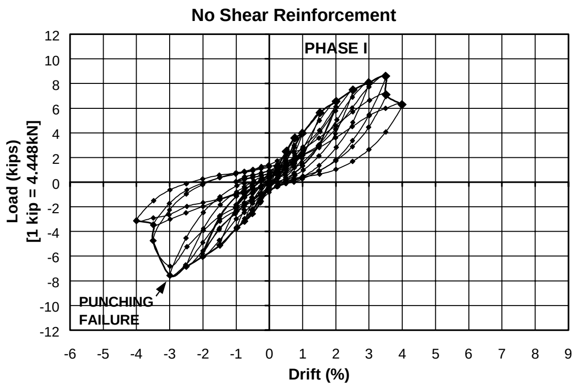
Figure 8: Punching shear failure, 1C.

Figure 9: Specimen 2CS at 8% drift.

Figure 10: Specimen 4HS at 8% drift.

Load-Drift Relationships

The load-drift hysteresis loops for each of the four tests are shown in Figures 11 to 14. The maximum lateral load sustained during each cycle is highlighted as part of a load-drift envelope superimposed on the hysteresis plots. These envelopes are then plotted for all four specimens in Figure 15 for easier comparison.



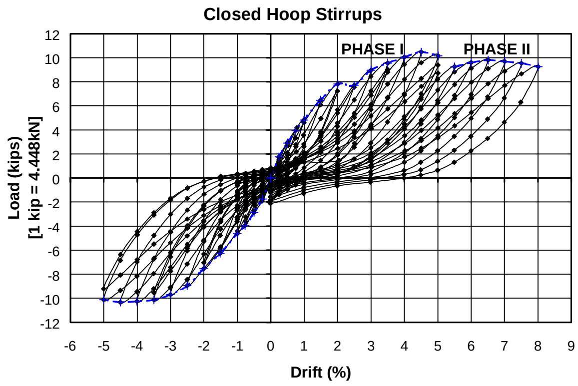
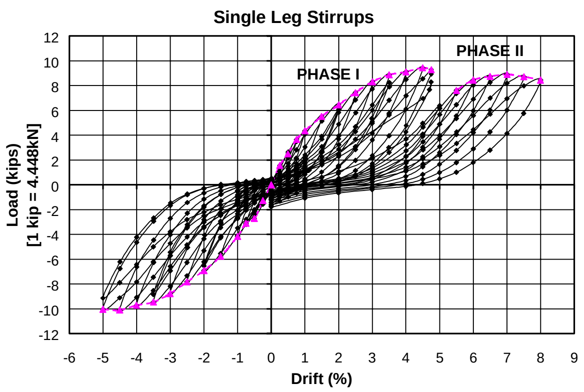


Figure 11: Specimen 1C, load vs drift.

Figure 12: Specimen 2CS, load vs drift.

The punching shear failure of specimen 1C is indicated in Figure 11 by the sudden drop in lateral load capacity during the 3.5 percent drift cycle in both positive and negative directions. All specimens with slab shear reinforcement were able to resist punching shear failure and sustain lateral drifts as high as 8 percent with less than 15 percent decrease in peak lateral load capacity.



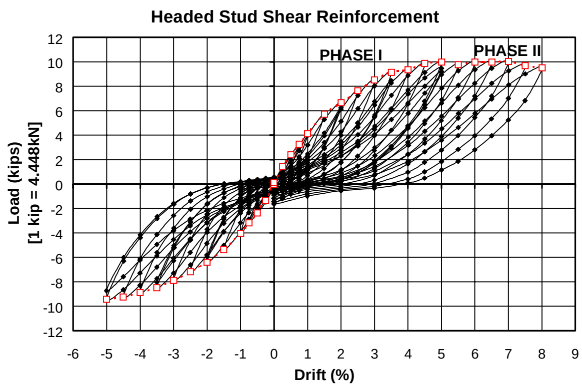


Figure 13: Specimen 1C, load vs drift.

Figure 14: Specimen 2CS, load vs drift.

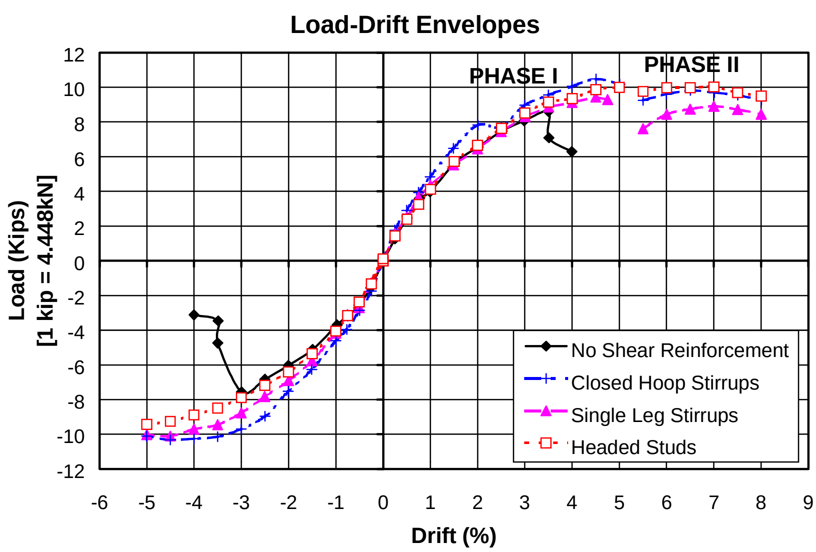


Figure 15: Load vs drift envelopes for all specimens.

CONCLUSIONS

All test specimens were able to withstand lateral drifts in excess of 3 percent prior to significant deterioration of the slab concrete around the slab-column connection.

The control specimen failed as a result of punching shear failure around the slab-column connection during the 3.5 percent drift cycle. None of the specimens with slab shear reinforcement experienced punching failure during testing to 8 percent lateral drift.

All three types of slab shear reinforcement proved equally effective in resisting punching shear failure of the slab-column connection. The specimens with slab shear reinforcement were able to sustain significantly larger lateral drifts than the control specimen, while maintaining gravity and lateral load carrying capacity. The simplicity of placement of the headed stud reinforcement makes it an attractive alternative to the single leg stirrups and the closed hoop stirrups (open hoop with closure clip).