RETROFIT OF FLAT-SLAB COLUMN CONNECTIONS USING CFRP STUDS TO RESIST PUNCHING-SHEAR FROM CYCLIC LOADING

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Abstract

Flat-slab construction has been and is still widely used in construction today because of the many advantages that it offers. The use of flat-slabs in multi-story apartment buildings and business centers for example, allows for more flexibility with architectural design, more open interior spaces, lower floor-to-floor heights, easier formwork, and shorter construction times. However, despite these advantages, flat-slabs, depending on their design (i.e. concrete strength, reinforcement layout, slab depth, etc.), can be susceptible to punching shear failure around the slab-column connections. Punching shear is caused by the transfer of shear forces from the slab to the column connections. Excessive gravity loads and/or unbalanced moments at the slab-column connections experienced during events such as earthquakes have often precipitated punching shear failure. This in turn can lead to progressive collapses throughout a building from floor to floor in a “pancaking” effect.

This report introduces an experimental test on the effectiveness of the use of Carbon Fiber Reinforced Polymer (CFRP) studs as a viable retrofitting method/device to help increase the punching shear capacity and ductility of concrete flat slabs (at their slab-column connections) during a cyclic loading event such as an earthquake. The layout of the CFRP studs was determined using the standards set in the ACI 318-05 Code. Two scaled specimens, a control slab (without studs) and an experimental slab (with studs), of a typical slab-column connection in a flat slab building were subjected to several cycles of quasi-static reverse-cyclic loads from a hydraulic ram until either punching occurred or the limit of the hydraulic testing apparatus was reached. The results showed that the CFRP studs were able to increase the retrofitted slab’s punching shear capacity and ductility by reaching the capacity of the testing apparatus at 10 percent drift without punching shear failure, compared to the control slab which experienced a sudden punching shear failure at 2.9 percent lateral drift.
Acknowledgements

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Introduction

1.1 Flat-slab Advantages & Shortcomings

Concrete flat-slabs have been used since the mid 1900s and are one of the most common floor systems employed in the construction of many multi-story buildings such as offices, hotels, and apartments throughout the world (See Figs. 1 & 2). In terms of design, flat-slabs offer almost a blank canvas for the architect and a very flexible interior layout. By not having any deep beams taking up space and/or protruding through the slab soffit/ceilings, it offers more clear space, and does not get in the way of any mechanical components such as air conditioning ducts, electrical wiring, and plumbing. Also, false/drop ceilings do not have to hang so low to hide the mechanical/electrical/plumbing components, which in turn can either translate to a smaller building height or an increase in the number of building floors available while still within the height restrictions of a particular zone. In terms of construction, flat-slabs have much easier and simpler formwork, and the same form can be used multiple times for several if not all the floors of a building.
This in turn presents a much shorter construction time allowing all trades of the construction of the building (painters, electricians, plumbers, decorators, etc.) to complete their portions of work much sooner as well. This results in quicker turnaround between construction and use of the building where tenants can start moving in and the building can begin to generate revenue.

However, flat-slabs, depending on their design layout (i.e. concrete strength, reinforcement layout, slab depth, etc.), are susceptible to punching shear failure around the columns. Punching shear failure can be caused by the transfer of shear forces from the slab to column connections. These shear stresses which cause the failure can come from excessive gravity loads around a slab-column connection due to increases in dead and/or live loads over those for which the building was designed for (i.e., building usage change from an office building to a storage facility). The shear stresses can also be caused by unbalanced moments from a combination of gravity loading and lateral deflections or movement experienced during events such as earthquakes and high winds. Once these shear stresses exceed the slab’s shear capacity, punching occurs, and depending on the severity/intensity of the event, can happen with little or no warning.

Because many buildings that employ flat-slabs are greater than two stories, punching shear failure can not only cause a building to lose its structural integrity at the slab column connection, but it can also lead to a progressive collapse from floor to floor throughout the building in what seems like a “pancaking” effect (see Fig. 3). Even at floors where the slab-column

Figure 3 – Progressive floor collapse of a building during the 1985 Mexico City Earthquake
connections are still somewhat intact, they become more and more susceptible to punching as the weight of the floors above progressively increase the load on the connection as more and more floors collapse. This kind of progressive collapse failure was witnessed during the 1985 Mexico City Earthquake, which measured 8.1 on the Richter scale, because quite a few of the buildings constructed in Mexico City at the time were flat-slab buildings. One building of note was the Juarez Hospital, a 12-story flat-slab building, which was severely damaged because of the progressive collapse of its floors, as shown in Figure 4, due to punching shear failure. Similar building collapse failures have occurred in other seismic incidents such as the 1994 Northridge, California Earthquake and the 1999 Kocaeli, Turkey Earthquake.

Figure 4 – Juarez Hospital after the 1985 Mexico City Earthquake
1.2 Possible Retrofitting Methods

To help increase the punching shear capacity of flat slabs, there are several possible retrofitting methods available. Each of the different methods comes with their own advantages & disadvantages as well as methods of installation. Depending on the situation and the type of building involved (i.e., office, apartment, storage, etc.), some methods are more desirable than others.

**Built-Up Column Sections – Column Capitals & Drop Panels**

Column capitals and drop panels, as shown in Figure 5, are essentially built-up or thickened sections of concrete at the top of columns (or lower side of a flat slab). Column capitals are wider at the top and taper down towards the column. Drop panels are a uniform thickness of concrete added to the soffit of the slab around the column. Drop panels can also be extended along column lines as shallow beams connecting columns throughout a building’s floor/ceiling plan. By increasing the depth and the area of the critical shear section at the slab-column connection through the addition of column capitals and/or drop panels, the shear capacity around the column is increased.

The construction of cast-in-place column capitals and drop panels is very time consuming and labor intensive, and invasive for building occupants. These built up sections also increase the overall weight of the slab, and potentially reduce valuable interior space.
Steel Plates and Bolts

The use of steel plates around a column at the top and bottom of a flat slab held in place with bolts that go through the slab (Fig. 6) has been shown to increase the shear capacity of the slab-column connection and extends the critical perimeter for punching around the column (Ebead and Marzouk 2002).

The use of steel plates and bolts does not take up much interior space, and the installation process is relatively simple. However, the plates on the slab top surface will interrupt the floor finish and potentially create a trip hazard. Installation of the steel bolts will require numerous relatively large holes to be drilled through the slab close to the slab-column connection.

![Figure 6 – Steel plates with bolts through concrete slab](image)

Steel Collars Around Columns

The use of steel collars around columns (Fig. 7) serves a similar function as a concrete column capital by increasing the punching shear critical perimeter/zone around the column, and it also acts as exterior shear reinforcement around the slab-column connection. The steel collars, which are bolted into the column and into the slab soffit above, can act as a platform to “catch” the slab and prevent a progressive collapse of the floor above.
However, depending on the size of the column being retrofitted, the steel components that make up the collar can be very large and just like the built-up sections, take up valuable interior space. The installation of steel collars requires large dowels to be drilled into the existing columns as well as through the soffit slab of the floor above.

**Fiber Reinforced Polymer (FRP) Stirrups**

Fiber reinforced polymer (FRP) stirrups installed in a wet-layup procedure as shown in Figure 8, have been shown to increase the punching shear capacity of slab-column connections (Binici and Bayrak 2005). The use of FRP materials offers many advantages such as a high strength to weight ratio of the materials used and a relatively easy installation procedure. However, in the case of FRP stirrups, relatively large holes are needed to accommodate the threading of the FRP tows through the slab to form the insitu-stirrups.
2.1 Previous Research Studies at UH Manoa

There have been previous research studies/experiments that have taken place at the University of Hawai‘i at Manoa in regards to the performance of concrete flat-slabs and their slab-column connections. One previous study looked at the performance of flat-slabs that contained either no reinforcement at the slab-column connection, closed hoop stirrups, single leg stirrups, or headed studs (Robertson et al 2002) as they were subjected to combined gravity and cyclic lateral loading. It showed that the control specimen experienced a punching shear failure at the slab-column connection at a drift of 3.5 percent, while the other three specimens were tested to 8 percent drift and had experienced no punching failure.

A second study expanded on the one previously mentioned and continued the research by taking the specimens tested in the previous experiment, only those that had shear reinforcement, and repaired them using epoxy crack sealers and Carbon Fiber Reinforced Polymer (CFRP) sheets on the surfaces of the slabs (Johnson and Robertson 2004). After repairing the slabs, the specimens were then subjected to an increasing cyclic lateral loading routine up to 8 percent lateral drift. It was found that the use of both epoxy and CFRP sheets for the repair on the top surface of the specimens helped to restore both their initial stiffness and ultimate strength.

A third study investigated the responses of several slab-column connections with different arrangements of discontinuous slab reinforcements as well as different gravity loading situations (Johnson and Robertson 2006). From the six slabs that were subjected to cyclic lateral loading during this experiment, the results were used to create a model to estimate the lateral drift at which punching failure may occur.
Proposed Retrofit Solution

3.1 Use of CFRP Studs

The proposed goal for the use of CFRP studs in the retrofit of concrete flat-slabs, much like the aforementioned methods, is to increase the punching shear capacity of the slab-column connections, and at the same time overcome many of the disadvantages that the previous methods posed such as an increase in overall weight around the connection, loss of interior space, and relatively time consuming installation/construction periods.

3.1.1 CFRP Stud Materials and Characteristics

The main components used to create the CFRP studs are the same as previous experiments done at the University of Hawai‘i at Manoa (Johnson and Roberson 2004, 2006):

- Sika Wrap Hex 103C: a high strength, unidirectional carbon fiber fabric
  - Tensile strength = 5.5 x 10^6 psi (3,793 MPa)
  - Tensile modulus = 34 x 10^6 psi (234,500 MPa)
  - Elongation = 1.5 percent

- Sikadur 300: two-component 100 percent solids epoxy
  - Tensile strength = 8,000 psi (55 MPa)
  - Tensile modulus = 2.5 x 10^5 psi (1,724 MPa)
  - Elongation = 3 percent

When used together as a system, with the epoxy used to impregnate the carbon fiber and hardening it, they achieve the following average property values:

- Sika Wrap Hex 103C + Sikadur 300 (per manufacturer’s test data & procedures)
  - Tensile strength = 123,200 psi (849 MPa)
  - Tensile modulus = 10.24 x 10^6 psi (70,552 MPa)
  - Elongation = 1.12 percent

This information and other technical material properties/data, as well as mixing instruction and MSDS sheets can be found and downloaded on the manufacturer’s (Sika USA) website, www.sikaconstruction.com. In addition to this experiment, information on the performance of the
CFRP studs from previous experiments has been documented in a recent study (Hayashi and Robertson 2008).

3.1.2 CFRP Stud Fabrication

The Sika Wrap Hex 103C carbon fiber sheets are rolled into rods and the top half of the rods are placed into plastic shrink wrap tubes, which are then heated to conform tightly around the fibers and to protect them from being coated with epoxy at this stage. The remaining exposed fibers of the rods are then impregnated with the Sikadur 300 epoxy and placed into metal stud forms (see Fig. 9). A couple of inches of the carbon fiber sheet rods are left outside of the bottom of the form to be used to create the base of the stud by splaying out the fibers. Smaller rectangular pieces of carbon fiber sheets are used to reinforce the base of the stud by being sandwiched between the splayed fibers. The entire assembly is then placed in an oven to cure for about a day. Once the epoxy has cured and hardened, the carbon fiber rods are then stripped from their molds and their rectangular bases trimmed into a more circular shape (see Fig. 10). A more comprehensive fabrication procedure can be found in a separate study coinciding with this experiment (Hayashi and Robertson 2008).

Figure 9 – Finished CFRP stud

Figure 10 – Carbon fiber sheets rolled into a rod with metal stud form
Construction of Slab Specimens

4.1 Dimensions, Materials and Methods

In this study, two specimens of reinforced concrete slab-column connections were used during the testing. One specimen was used as a control with no CFRP studs and the other was used as the retrofitted specimen. Each specimen was a half-scale model of a typical interior connection found in a flat-slab building. The slabs are similar in design, construction and dimensions as those previously tested in the earlier studies at the University of Hawai‘i at Manoa (Robertson et al 2002, Johnson and Robertson 2004, 2006). For identification purposes, the two slab specimens have the following designations:

<table>
<thead>
<tr>
<th>Slab</th>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>RCC</td>
<td>Control slab specimen</td>
</tr>
<tr>
<td>Retrofit</td>
<td>RCCFRPST</td>
<td>Retrofitted slab specimen with the CFRP Studs</td>
</tr>
</tbody>
</table>

Note: RC stands for Reverse Cyclic

4.1.1 Concrete Slab Specimen Dimensions and Materials

The dimensions and layout of the two slab specimens that were tested are shown in Figures 11 and 12. For the control slab specimen, RCC, the approximate strength (f’c) of the concrete used was 6,500 psi, while the concrete for the retrofitted slab specimen, RCCFRPST, was approximately 4,000 psi.
Figure 11 – Elevation view of slab specimen

Figure 12 – Plan view of slab specimen
4.1.2 Concrete Slab Specimen Reinforcement Details

For the slab specimens, the steel reinforcement used was fairly light and consisted of a double mat of #3 bars around the column connection. However, much like the flat-slabs constructed in the 1970s and 1980s, the bottom mat of steel reinforcement used mostly discontinuous bars that did not tie into the column. The steel reinforcement used in the slab specimens was ASTM Grade 60 deformed bars. The layout of the top and bottom reinforcing steel are shown in Figures 13 and 14.

Figure 13 – Top reinforcement plan view
4.2 Description of Test Slab Specimen Retrofit

4.2.1 Layout & Installation of CFRP Studs

The layout and spacing of the CFRP studs for slab specimen RCCFRPST were based on the specifications given in the ACI 318-05 code. Therefore, as shown in Figure 15, the pairs/rows of studs were spaced no more than 0.75d on center from each other, the pairs closest to the face of the columns were placed 0.5*(0.75d) away from the face, and seven (7) pairs of studs were chosen so as to extend past the critical perimeter around the column connection of 0.5d. In this case, d was the measurement of the average effective depth from the bottom of the slab to the top of the tension steel reinforcing, which was approximately 3.75". Also, the studs were kept within the confines of the edges of each of the faces of the column, and some leeway was given for the placement of the studs within the aforementioned parameters to avoid the underlying rebar (which were located using a rebar locator).
Once the locations of the studs were determined, 3/8” diameter holes were drilled for the studs and the slab surfaces around and in between the studs were roughened using a needle gun/scaler. The surface of the slabs were then swept clean of any dust and debris, and the CFRP studs were placed through the holes from the bottom of the slab with the tips extending through the top of the slab (Fig. 16). The gaps between the base of the studs and the soffit of the slab were filled with a two-component, high strength structural epoxy paste adhesive, Sikadur 30 (Fig. 17), and allowed to cure overnight. Next, a primer coat of Sikadur 300 epoxy was placed on the roughened top surface of the slab around the studs. The epoxy was also used to fill any spaces between the holes in the slab and the studs. Strips of the Sika Wrap Hex 103C sheets were placed outside and in between the studs and the tips of the studs were splayed out onto the sheets (Fig. 18). Another sheet was then placed on top of the splayed stud fibers and bottom sheet of carbon fiber and a final coat of epoxy
was applied. Any air bubbles were smoothed out and the epoxy was left alone to set overnight. A more detailed installation procedure can be found in a separate study coinciding with this experiment (Hayashi, 2008).

4.2.2 Position and Loading of Weights

The two slab specimens were loaded with weights around the slab column connection to the point where the gravity shear ratio (GSR) of each slab was around the same ratio or greater as the slab specimens previously tested (Johnson and Robertson 2004).

To help ensure that the weights around the slab column connection were loaded evenly, each slab was divided into four quadrants and loaded in a criss-cross pattern. Table 2 shows the different types of items that were used to load the slabs and their total weights. The kinds of things used to
apply weight to the slabs ranged from 1-1/4” to 3-1/2” diameter steel rods, concrete slabs/blocks, miscellaneous steel plates and even concrete benches from outside of the testing lab (Fig. 19 and 20). Due to the disparity between the concrete strengths of the two specimens (RCC = 6,500 PSI vs. RCCRPST = 4,000 PSI), additional weight was added to specimen RCC.

Table 2 – Slab Weights Loaded onto Specimens

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>Slab Weights (LBS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel Round Bar</td>
</tr>
<tr>
<td>RCC</td>
<td>6314.1</td>
</tr>
<tr>
<td>RCCRPST</td>
<td>6314.1</td>
</tr>
</tbody>
</table>

Figure 19 – Loaded slab specimen RCC
Figure 20 – Loaded slab specimen RCCFRPST
5.1 Test Setup/Instrumentation & Routine

3.1.1 Testing Apparatus & Instrumentation

The test setup & instrumentation, which were the same as previous experiments, for the two slab specimens are shown in Figure 21. The points of inflection were assumed at mid height of the columns, both above and below the slab specimens, and at the mid span of the slabs on either side of the column. The base of the column was attached via a pin connection to the existing laboratory strong floor. At this connection, two load cells were attached, one vertical to measure the gravity load on the slab and one horizontal to measure the lateral load (Fig. 22). The slab edges were supported by load rods (Fig. 23) that were also connected to the strong floor. These load roads were pin connected at the top and bottom allowing horizontal movement of the slab during testing but restricted any vertical movement. The locations of the load rods are shown in Figure 12. The top of the column was attached/pin-connected to a hydraulic pump and horizontal hydraulic actuator (servo-controlled...
MTS Unit) with a horizontal load cell at the end (Fig. 24). The actuator and a digital controller applied the displacement routine (drift) to the slab specimens while the load cell measured the lateral loads applied to the column. Strain gauges were also connected to portions of the reinforcement found in the slab specimens. A data acquisition system/program recorded all of the instrumentation readings.
5.1.2 Testing Routine (Cyclic Loading)

The slab specimens were subjected to an increasing cyclic displacement routine as shown in Figure 25. To achieve this routine, the hydraulic ram connected to the top of the column would push and/or pull to a certain drift level depending on the cycle. One cycle is represented as a push to a drift level of lets say 3 percent, a return to center or zero, a pull to a drift of -3 percent (negative because it is in the opposite direction from the first push), and then a return to center or zero. This cyclic loading routine was used from 0.25 percent to 5 percent drift levels. Then, because of the current limitations of the hydraulic ram’s stroke, only one half of the cycle (the positive direction) was used for the drift levels above 5 percent. Also, again due to the limitations of the hydraulic ram, a drift level of 10 percent was the maximum direction. However, only slab specimen RCCFRPST was tested this high.

Figure 25 – Reverse cyclic displacement routine
5.2 Test Results

5.2.1 Slab Specimen RCC

Figure 26 – RCC Specimen with hysteretic response & backbone curve

Figure 26 shows the hysteretic response along with its backbone curve of slab specimen RCC. It shows that slab specimen RCC, which was the control specimen with no CFRP stud retrofit around the slab-column connection, survived one cycle at 3 percent drift before punching during the second cycle. The maximum lateral load during the test was 8.1 kips.
5.2.2 Slab Specimen RCCFRPST

Figure 27 - RCCFRPST Specimen with hysteretic response & backbone curve

Figure 27 shows the hysteretic response along with its backbone curve of slab specimen RCCFRPST. It shows that specimen RCCFRPST, which was the retrofitted specimen with the CFRP studs around the slab-column connection, achieved a maximum drift of 10 percent (the maximum drift limitation due to the stroke of the hydraulic ram), and a maximum load of 8.4 kips. This specimen did not experience any punching shear failure, however, it did experience a flexural failure as it was not able to attain 80 percent of its peak lateral load.

5.2.3 Overall Test Results

The following figures (Figures 28 and 29) show the hysteretic responses and backbone curves, respectively, of both slab specimens overlaid over each other.
Figure 28 – Hysteretic response of both slab specimens (RCC vs. RCCFRPST)

Figure 29 – Hysteretic backbone curves of both slab specimens (RCC vs. RCCFRPST)
Analysis & Discussion

6.1 Analysis

As shown in the test results of the two slab specimens tested, the retrofitted slab specimen, RCCRFISPST, outperformed the control specimen, RCC. Slab RCCRFISPST was able to attain a slightly higher maximum horizontal load of approximately 8.4 kips versus the 8.1 kips of slab RCC. It also was able to go through the entire cyclic loading routine to 10 percent lateral drift, without experiencing any punching shear failure (it did have a flexural failure), while slab RCC experienced a punching shear failure at 3 percent drift.

Specimen RCCRFISPST had a gravity shear ratio of 0.33 at its maximum attained drift of 10 percent compared to specimen RCC’s gravity shear ratio of 0.35 prior to failure at 3 percent drift. When compared to the slab specimens tested in previous experiments (Johnson and Robertson 2006), whose designations and descriptions are given in Table 3, these gravity shear ratios fall between those for specimens ND4LL and ND5XL, both of which failed in punching shear. As Table 4 shows, slab RCCRFISPST was able to achieve higher drift levels and horizontal loads compared to slabs specimens ND1C, ND4LL and ND5XL. Figure 30 shows a comparison of the five slab specimens’ hysteretic backbone curves.

Table 3 – Previously tested slab specimen designations and descriptions

<table>
<thead>
<tr>
<th>Slab Specimen Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND1C</td>
<td>Control specimen</td>
</tr>
<tr>
<td>ND4LL</td>
<td>Identical to ND1C but increased slab loading (LL = light load)</td>
</tr>
<tr>
<td>ND5XL</td>
<td>Identical to ND1C but with greater slab loading than ND4LL (XL = extra large load)</td>
</tr>
</tbody>
</table>

Note: All slab specimens, including RCC & RCCRFISPST are identical to slab ND1C in terms of dimensions and reinforcing.
### Table 4 – Slab specimen test data summary

<table>
<thead>
<tr>
<th>Test Results</th>
<th>Specimen</th>
<th>ND1C</th>
<th>ND4LL</th>
<th>ND5XL</th>
<th>RCC</th>
<th>RCCFRPST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gravity load at failure, $V_{gf}$ (kips)</td>
<td>ND1C</td>
<td>12.4</td>
<td>15.9</td>
<td>22.8</td>
<td>23.3</td>
<td>17.5*</td>
</tr>
<tr>
<td>2. Failure gravity shear ratio, $V_{gf}/V_o$</td>
<td>ND4LL</td>
<td>0.23</td>
<td>0.28</td>
<td>0.47</td>
<td>0.35</td>
<td>0.33*</td>
</tr>
<tr>
<td>3. Maximum positive horizontal load (kips)</td>
<td>ND5XL</td>
<td>6.4</td>
<td>7.0</td>
<td>5.1</td>
<td>8.1</td>
<td>8.4</td>
</tr>
<tr>
<td>4. Maximum negative horizontal load (kips)</td>
<td>RCC</td>
<td>-6.9</td>
<td>-7.3</td>
<td>-5.3</td>
<td>-7.1</td>
<td>-7.9</td>
</tr>
<tr>
<td>5. Positive drift at maximum horizontal load (%)</td>
<td>RCCFRPST</td>
<td>3 to 5</td>
<td>3</td>
<td>1.5</td>
<td>2.8</td>
<td>4.8</td>
</tr>
<tr>
<td>6. Negative drift at maximum horizontal load (%)</td>
<td>ND1C</td>
<td>-3</td>
<td>-3</td>
<td>-1.5</td>
<td>-2.8</td>
<td>-4.9</td>
</tr>
<tr>
<td>7. Maximum drift attained before failure (%)</td>
<td>ND4LL</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>10*</td>
</tr>
<tr>
<td>8. Type of failure</td>
<td>ND5XL</td>
<td>Flexure/punch</td>
<td>Punch</td>
<td>Flexure/punch</td>
<td>Flexure</td>
<td></td>
</tr>
</tbody>
</table>

*Values shown for first cycle to 10 percent drift

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**Figure 30 – Hysteretic backbone curves of all slab specimens**
6.2 Discussion

The use of CFRP studs was successful in increasing the ductility and the punching shear capacity of the retrofitted flat slab specimen. The retrofitted connection’s overall performance compared with the control specimen and previous slab specimens is evidence to indicate that the CFRP headed studs are a viable retrofit solution. Their low weight-to-strength ratio makes them a much more practical solution over steel plates with bolts and built up concrete sections. Because they are relatively light and easy to handle, the installation of the CFRP studs is simple and comparatively quick. They require very few pieces of equipment (i.e., needle gun, drill, roller and mixer), relatively small amounts of material (i.e., studs, epoxy, carbon fiber sheets and concrete patch material), and a reduced work/labor crew for installation. With a quick installation time, this would result in very little downtime, especially for buildings that have many tenants. They can be quickly installed onto selective and/or isolated slab-column connection areas, such as areas of increased loads or vital areas of a building’s frame (interior slab-column connections).

Compared to the other possible retrofitting methods, the CFRP studs are much more aesthetically pleasing. With its fairly flat installation profile on the slab surface, it would not interfere with the floor elevations and can be easily covered by carpeting and/or some other type of floor finish. Also, unlike some of the other retrofit methods, there is no loss of valuable interior space.

Because of the limited scope of this study with only two slabs and one arrangement of studs, there is potential for further research. As shown in the results, the CFRP studs are technically feasible as a possible retrofitting method. However, the cost effectiveness of this method was not determined. This could be a very important aspect towards choosing this method over others, especially with the current state of the world economy, rising material costs, and a shortage of carbon fiber material because of demand. Would the benefits outweigh the costs of the materials and installation? A few key areas that could be looked at are the stud’s manufacturing costs, overall material costs, design and construction costs.
Another area of further research could be geared more towards the studs themselves. A different stud diameter and shape of the base of the studs could possibly promote better adhesion between the slab, epoxy resin and the studs themselves. The installation methods/procedures could also be revised so that it is more efficient and uniform. In this study, the seven (7) pairs of studs at each column face was able to prevent punching shear failure. Perhaps there are other configurations that might be able to produce the same results if not better.
Summary & Conclusions

The use of carbon fiber reinforced polymer (CFRP) studs to retrofit the slab-column connections of concrete flat slabs to help resist punching shear from cyclic loading is presented in this report. Guidelines from the ACI 318-05 provisions were used to help determine the layout of the CFRP studs around the slab-column connections. Comparisons to the results of previous experiments at the University of Hawai‘i at Manoa were used to determine the effectiveness of the retrofitting method.

Based on the results of this study, the following conclusions were drawn:

1. The use of CFRP studs helped to increase the ductility of a slab-column connection of a concrete flat slab compared with the control specimen. The retrofitted slab specimen (RCCFRPST) achieved a 10 percent lateral drift without a punching shear failure, while the control specimen (RCC) failed due to sudden punching shear at a lateral drift of 3 percent.

2. The installation of the CFRP studs was relatively easy compared to other retrofitting methods.

3. Because of its flat installation profile on the slab surface, there is minimal disruption to floor finishes/aesthetics and zero loss of interior space.

4. Installation time of CFRP studs was short which results in brief downtime for areas that may require retrofitting. This would be a viable option for buildings choosing to do selective and/or isolated slab-column connection areas only.

5. Results confirmed the technical feasibility of the use of CFRP studs as a retrofitting method. However, the cost effectiveness has yet to be determined. Key areas for possible future studies should look at CFRP stud manufacturing costs, overall material costs and construction costs (labor rates and field installation rates).
6. Due to a limited number of slab specimens and materials available, only one CFRP stud layout/arrangement was tested and although fairly successful in preventing punching shear, leaves the door open for research into other possible stud geometries and configurations.
References

ACI Committee 318. “Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05),” Reported by ACI Committee 318, American Concrete Institute, Detroit, Michigan.


Appendix

9.1 Additional Figures of Slab Specimen RCC

Figure 31 – Slab Specimen RCC Post Test Failure Pictures
9.2 Additional Figures of Slab Specimen RCCFRPST

Figure 32 - Slab Specimen RCCFRPST Post Test Failure Pictures
Figure 33 – Slab Specimen RCCFRPST Post Test overhead view w/cracks

Figure 34 – Cracking pattern for Slab Specimen RCCFRPST
9.3 Additional Information from Previously Tested Slab Specimens

**Figure 35 – ND1C Specimen with hysteretic response & backbone curve**

**Figure 36 – ND4LL Specimen with hysteretic response & backbone curve**
Figure 37 – ND5XL Specimen with hysteretic response & backbone curve