# Current Advances in FRP Anchorage Testing

2013 NZSEE
Conference

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**ABSTRACT:** The primary focus of this paper is to present examples of recent fiber reinforced polymer (FRP) anchor experimental testing, by summarizing the purpose, design concept of the FRP anchors and the results obtained from each testing program. In order to show a clear picture of the extent of research conducted on FRP anchors, it was vital to present case studies, which look at a variety of structural applications. There are four case studies presented ranging from uses of FRP anchors to: increase the flexural capacity of reinforced concrete columns, increase the shear capacity of bridge beams, increase the flexural strength of reinforced concrete shear walls, and use FRP anchors to mitigate progressive collapse. In the end, each study was able to identify a clear correlation between the increased performance of the tested specimens and the unique applications of the FRP anchors within each situation.

## 1 INTRODUCTION

The use of FRP anchors is a relatively new development in the world of structurally rehabilitating reinforced concrete (RC) structures. Over the past ten years, there have been an increased number of studies researching the effectiveness of FRP anchors, but still a design methodology is lacking (Ozdemir 2005). In order for an appropriate design methodology to be created, there needs to be continued testing on a variety of applications and scenarios. Even though there are published works describing the failure modes of FRP anchors and present equations, which can be used in determining their capacities, but there is still not enough information on the design of unique applications and proper detailing of FRP anchors (Kim & Smith 2010).

The focus of this paper will be on four case studies from research institutions, all over North America, whose goals were to test a variety of FRP anchor designs and applications. The first case study investigated how the use of FRP repair systems and the use of FRP anchors to aid in strengthening RC bridge columns. While the second case study considers the effect of including FRP anchors into the shear strengthening of bridge beams. Then the third case study investigates the use of FRP anchors to increase the flexural capacity of RC shear walls. Finally the fourth case study, considers how FRP anchors can successfully retrofit structures that are prone to progressive collapse stemming from inadequate detailing. Within each study, there discussions illustrate not only the design of FRP anchors, but also how the detailing and application of the FRP anchors is crucial for successful results.

## 2 CASE STUDY: REPAIRING DAMAGED REINFORCED CONCRETE COLUMNS

### 2.1 Purpose of the Study

In 2010, North Carolina State initiated a four-part testing program, which investigates the impact of FRP repair systems have on the strength of RC bridge columns. In order for the results to be representative of current conditions, all the columns were subjected to real earthquake time histories load data and each was repaired using FRP. In each part of the testing program, a different aspect of the repair system was analysed. Nevertheless looking specifically at the goals of part 2, the design was developed based on the outcomes from part 1 where only FRP confinement was provided and inadequate results were obtained. This part of the study focused primarily on the design and implementation of the carbon fiber-reinforced polymer (CFRP) anchors.

Ultimately, it was determined that the relocation of the plastic hinge was necessary. This allowed the plastic hinge to be relocated outside of the damaged footing interface region, which caused the failure to occur where the longitudinal reinforcement still had sufficient strain capacity. The aforementioned goal was achieved by applying the CFRP strips both horizontally and vertically with the addition of CFRP anchors embedded into the column footing and splayed onto the column itself.

### 2.2 **Design of FRP Anchors**

For the design of the CFRP anchors, their purpose was to force the plastic hinge region to the upper 38 cm of the column, which meant the base of the column needed to be strengthened to remain elastic. Consequently, this meant incorporating not only CFRP anchors but also vertical CFRP strips.

In the end, the size and length of the CFRP anchors was determined by performing a moment-curvature analysis of the column. The objective of the analysis was to determine the quantity of CFRP needed to keep the same displacement magnitude (from the results of part 1) at the top of the column. This analysis included a confinement model, which comprised the effects of both the steel spiral reinforcement and the CFRP strips in the hoop direction. The results of the moment-curvature analysis showed three layers of the vertical CFRP and 12 CFRP anchors, with a 3.18 cm diameter and embedded 35.6 cm into the footing with a 35.6 cm splay onto the column, was needed to meet the new required design moment.

In order for a sufficient bond to be achieved between the vertical CFRP and the carbon fiber anchors, the repair process was conducted over a two day period. In figure 1, the installation process and the rebar and CFRP anchors configurations are shown.

Figure 1: Configuration (a), saturation (b) and installation (c) of carbon fiber anchors

### 2.3 **Significant Results**

Once the specimens had reached their ultimate load capacities, the FRP repair system was removed to see the condition of the concrete surface following the test. A correlation was observed between the creation of the flexural cracks at the base of the column and where the separation of the fiber occurred.

Looking specifically at the CFRP anchors, ruptures occurred on each side of the column at NA4 and SA3, while anchor (NA2) did not reach its full strength due to inadequate embedment length at the time of installation. While for all the CFRP anchors, the careful detailing and surface preparation proved effective, since there was sufficient bonding, i.e. no delamination, between the CFRP strips and the CFRP anchors. One other noticeable observation was spalling of the concrete cover. This was directly related to an increase in the shear capacity (provided by the anchors) caused the footing to receive a higher shear force, which directly led to spalling of the concrete cover and resulted in large cracks in the footing.

Based on the results from Figure 2, it can easily be stated that the repaired specimen from part 2 outperformed the repaired specimen from part 1. Furthermore, comparing the results from part 2 directly with a virgin (unrepaired) column, the repaired column was able to withstand peak forces 20% higher than the virgin column. This implies the CFRP anchors in combination with the vertical CFRP strips are an effective repair technique for the column. From Figure 2 it is apparent, that from earlier ductility levels the column did begin to rotate about the new plastic hinge as desired, but as the test continues there is evidence that the footing is beginning to soften. Once this occurs, the concrete cover at the footing spalls off and there is nothing to contain the anchors and longitudinal reinforcement in the footing. In the end, the use of the FRP anchors and FRP strips to aid in increasing the lateral load, while not signficantly changing the ductility of the column, was achieved and proved very effective. The inclusion of the anchors into the repair design is crucial to provide the required confinement and achieve the desired results.

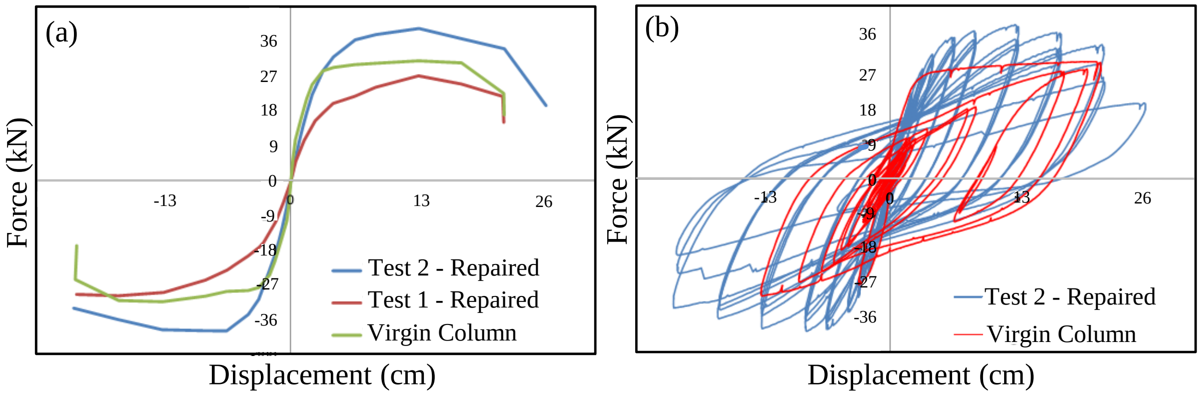

Figure 2: Comparative results of Force vs. Displacement Envelope (a) and Hystersis Loops (b)

## 3 CASE STUDY: SHEAR STRENGTHENING OF REINFORCED CONCRETE BEAMS

### 3.1 Purpose of the Study

Researching shear strengthening of reinforced concrete beams is not necessarily a new topic, but is a developing research focus. Previous studies have shown the application of FRP will strengthen the shear capacity of a beam. However, the only means for the shear forces to be transferred to the FRP is through the interface bond to the concrete substrate. This bond is the weakest element of the FRP strengthening system and reduces the tensile loads by 40% or 50% of their ultimate capacities. This undesirable debonding failure can be reversed with the use of FRP anchors (Wang et al 2000).

In 2010, a research program was created at the University of Texas at Austin, which investigated the shear strengthening of large bridge girders (or supporting elements) using a combination of CFRP and CFRP anchors. There are two main reasons for using CFRP and CFRP anchors to strengthen bridge beams: 1) repair or strengthening due to distress from overloads and 2) strengthening to increase the load capacity (Kim et al 2012). Considering the lack of design guidelines available for CFRP anchors, it is necessary for advanced testing to be conducted on large specimens to understand how they can carry the substantial shear forces.

### 3.2 Description of the Anchorage Detail

In total, 24 T-beam monotonic tests were conducted, where the tests were broken down into two sets, shown in Figure 3a and 3b. Each bridge beam was designed to have the minimum transverse requirements provided by both ACI 218-08 and NCHRP Design requirements. In order to investigate how the additional anchorage increases the shear capacity of the retrofitted beam specimen, a variety of CFRP strips (one or two layers) and CFRP anchor (one or two anchors every 12.7 cm) configurations were tested. However, the focus of the next section will be primarily on the results comparing directly the effect of additional anchorage had on the shear capacity of the bridge beams.

### 3.3 Significant Results

In Figure 3, the results were shown for both specimen 24-3-9 and 24-3-ref, which were tested without and with CFRP anchors, respectively. It is interesting to note, that the initial response for the unanchored (24-3-9) and the anchored (24-3-ref) beam was similar. Once a CFRP strip started to debond from the 24-3-9, this is when the beam stiffness was reduced, but when the applied load dropped off, this is when the CFRP fully debonded from the concrete at a strain of 0.004. The comparative strength gain was only 16.9 for the unanchored test, while the anchored test was 206 kN. The debonding failure is the main reason for the smaller shear gains, but also the lower ultimate deformation of the unanchored specimen at failure was also to blame.

In the end, for all the tests where CFRP was applied without anchors there was only an average of a 5% increase in the shear strength. While for the anchored specimens an increase in the shear capacity was on average 50%. The CFRP anchors were able to allow the CFRP strips to reach their full capacity and fail due to rupture of the CFRP strip and not debonding. These results indicate that the bond between the CFRP and the concrete substrate, which controlled the design of the CFRP strips, is not as critical when CFRP anchors are included. Eliminating the possibility of failure due to debonding, which is highly variable, will produce a more reliable strengthening system. However, increased testing is necessary to definitely conclude the results presented above.

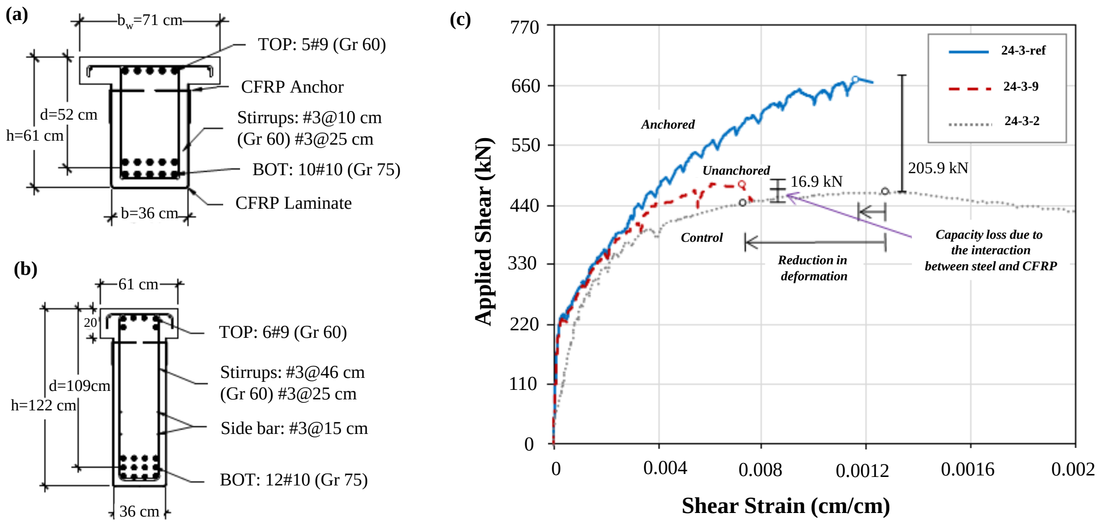

Figure 3: Test Specimen 1 (a), Test Specimen 2 (b), and results for both anchored and unanchored specimens (c)

## 4 CASE STUDY: SEISMIC RETROFIT OF REINFORCED CONCRETE SHEAR WALLS

### 4.1 Purpose of the Study

For many of the existing RC structures, the shear walls have been designed to be the primary element to resist the seismic forces. However, one main deficiency in these walls are the design codes used are older and are now the walls are seen as seismically deficient and need of a retrofitted. Some researchers have even noticed that newer design codes may be underestimating the shear demands at higher stories, which could be causing deficiencies in the shear walls (Priestley & Amaris 2002).

In 2012, Concordia University in Montreal initiated a testing program, which investigated this phenomenon of higher shear demands at higher stories. The main objective of this study was to understand the effectiveness of using externally bonded FRP to increase both flexural and shear capacities, when increased seismic loads are felt in the higher stories of RC shear walls. For this study, two 0.429-scale 8-story RC walls (see Fig. 4a) were first tested with no retrofit, then two different retrofit schemes were applied to the story recognized as having insufficient shear capacity. In both tests, the 6th floor was identified as the floor to be retrofitted due to the severity of the cracking and the yielding of the flexural reinforcement (El Sokkary et al 2012). This was in complete contradiction to design criteria, which followed NBCC (2005) and CSA A23.3 (2004) and deemed the floor seismically efficient. Even though many other parameters were also investigated in the program, the primary focus of the next sections will be the retrofit scheme and the corresponding results for the 6th floor only.

## 4.2 Design Approach for the 6th Floor

Using the results from the original walls, two different retrofit schemes were investigated and their designs are presented below. For each retrofit scheme, the design goal was to increase the walls moment capacity, by including the use of FRP anchors, to transfer the moment from the 6th floor to the floors above and below, 5th and 7th floors, respectively, while also increasing the shear capacity. To increase the moment capacity for each wall, a 200 mm wide vertical unidirectional CFRP strip was applied to the wall's extremities on both faces. Each retrofit was designed to make sure the factored flexural resistance was greater than the factored demand observed in the original tests. Finally, the shear capacity was increased through the use of one horizontal layer (on each face of the wall) of CFRP.

The difference between the two retrofit designs was in the detailing of the CFRP anchors. For both walls, the CFRP anchors were designed to the same ultimate capacity of 35% to take into account the strength reduction due to the bend of the fibers. In the end the CFRP anchors were designed to have a diameter of 12 mm. This assured that the vertical CFRP strips would rupture before the CFRP anchors would fail.

Looking specifically at the first retrofitted wall (W1), each of the vertical strips were anchored into the top and bottom slabs of the 6th story using CFRP anchors, approximately 200 mm long, which were fanned onto the wall. Each of the anchor holes were drilled at an approximate 30° angle with the wall surface, where the anchor was only embedded 60 mm into the slab above and below.

While for the second retrofitted wall (W2), the CFRP anchors were detailed differently (see Fig. 4b) due to the difficulty that was found in drilling the inclined holes through the wall web. This difficulty arose from the tight spacing of the wall's vertical reinforcement being concentrated around the wall's boundary columns, in the exact location where the CFRP anchors needed to be located. The use of this design approach allowed for a longer embedment length to be used for the CFRP anchors and the probability of the anchor debonding from the concrete substrate is reduced. In total each anchor was 360 mm long.

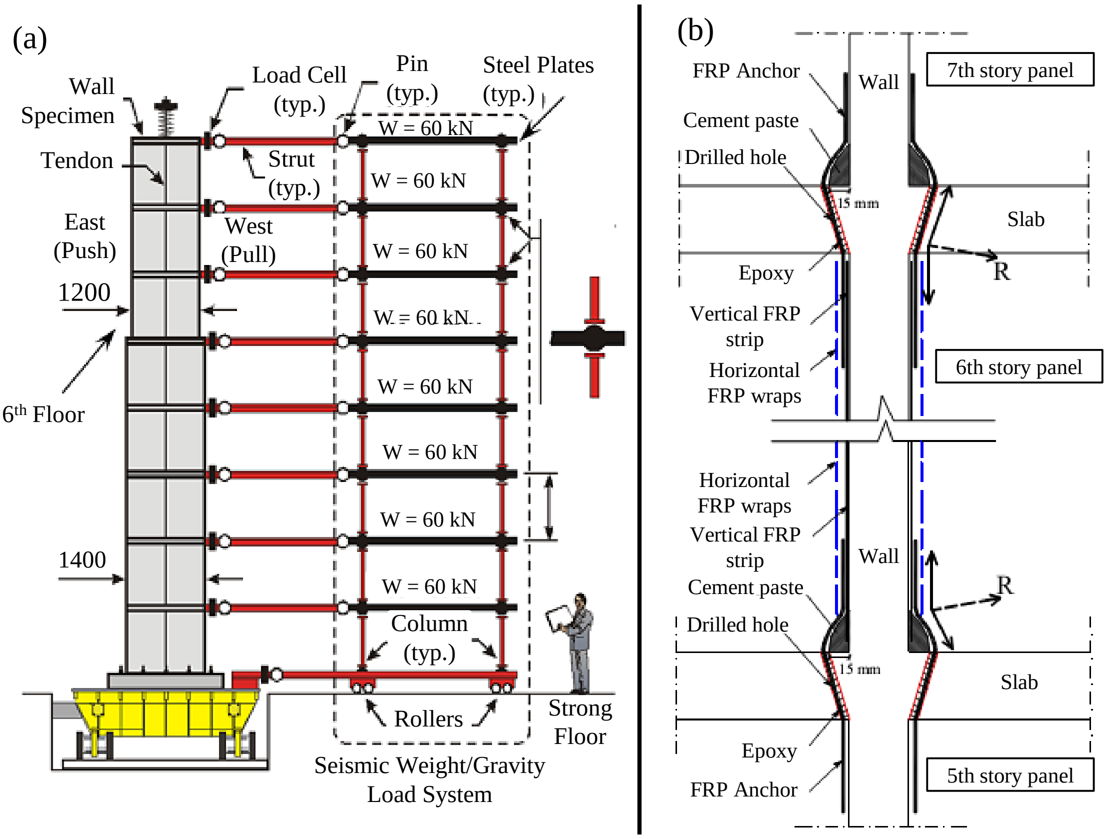

Figure 4: Testing specimen at half-scale (a) and Detail of Tyfo SCH Anchorage for Wall 2 (b)

## 4.3 **Significant Results**

For each specimen, there was testing conducted first without rehabilitation and then wrapped with their respective retrofit schematic and retested. For each of the rehabilitated walls, there was an increase in both the base shear and overturning moment. The increase is directly related to additional stiffness provided by the vertical FRP strips.

Looking deeper into the data, it was observed that the added CFRP strips reduced the maximum story rotation by 28% and 22% for W1 and W2, respectively. However, the moment demand on the walls at the 6th story increased slightly, but there was a reduction in the moment rotation. It is significant to note the walls were able to resist higher moment demands without increasing the rotational ductility demands, which is directly correlated to the effectiveness of the FRP rehabilitation scheme.

There was also a noticeable change in the inter-story drift ratios for each rehabilitated wall (-0.05% for W1 and -0.3% for W2). The change was more noticeable for the second wall, where the anchors were applied through the floors and onto the adjacent floors. The inter-story drift was reduced by 0.3% for the 7th floor and there was negligible change to the inter-story drift for the 5th floor. While it is interesting to note, that due to the higher moment demands coming from the rehabilitated structure actually caused the lower storeys to have increased inter-story drift ratios by almost 0.1% for some levels, but there was no significant change at the roof level.

During the push cycles for W2, there was almost no change observed in the wall's rotation after rehabilitation. This indicates that the vertical strips were not anchored properly to the slabs on the wall's west side. In contrast, for W1 the vertical CFRP strips applied to the sixth story panel were able to reduce the wall rotation in both the push and pull directions. Even though each anchor detail achieved its design capacity and successfully increased the moment demand of the shear wall, these results stress the importance of the proper detailing in the efficiency of FRP flexure rehabilitation of the system.

# 5 CASE STUDY: UNIQUE DESIGN OPTION FOR PROGRESSIVE COLLAPSE

## 5.1 **Purpose of the Study**

In 2006 the University of Texas at Austin began a study, which investigated improper detailing of the reinforcement at the bottoms of beams. For many of the RC structures built before the 1970s, the detailing for the bottom beam reinforcement is not continuous. As a result, the building is now vulnerable to progressive collapse, if it were to lose a column due to a possible terrorist attack or unexpected event. The main objective of the study was to investigate different CFRP options, which would to eliminate this detailing problem, but also allow the CFRP to reach its full tensile capacity and eliminate delamination (Kim et al 2006). The anchorage schemes were crucial for the second part of the design objective and included the use of both the CFRP anchors and CFRP U-Wraps (see Fig. 5).

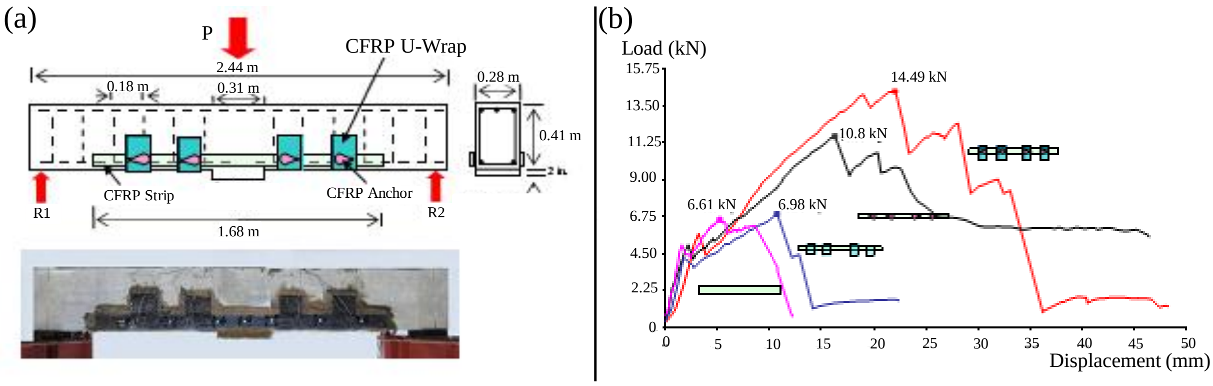

Figure 5: Test specimen 4 with anchorage detail (a) and Load vs. Displacement results for all the specimens (b)

### 5.2 **Design Parameters for the Experiment**

There were four different specimens created for this project, which were designed to both include and exclude the CFRP anchors and the CFRP U-Wraps. It became necessary to understand not only how the CFRP anchors assist in the allowing the CFRP strips to reach full tensile capacity, but how the specimens fail with a variety of anchorage details. In specimen 1 only CFRP sheets were applied to the bottom of the beam, while specimen 2 and 3 had a combination of CFRP with U-Wraps and CFRP anchors, respectively. Finally in specimen 4 (see Fig. 5a), the specimen was wrapped not only with the CFRP but also with both the CFRP anchors and the CFRP U-Wraps. The anchors were designed to help allow the CFRP to develop its full tensile capacity. As a result it was determined that eight 1.27 cm diameter anchors were required over the whole length of the beam.

All the specimens had a point load of 142 kN applied at the mid-span to represent the loading condition, where the column below has been removed. The added CFRP strips along the bottom of the specimen were designed to be equal to two continuous #6 rebar.

### 5.3 **Significant Results**

Looking specifically at the failure modes of each specimen, it was clear that the use of different anchorage schemes played a key role into the failure mode. For specimen 1 the goal was to maximize the surface area, which is the critical factor for bond capacity, of the CFRP strip since there was no additional anchorage applied. However, without the additional anchorage, the failure mode was still delamination of the CFRP strip. Even with the addition of the CFRP U-Wraps for specimen 2, it did not hold the CFRP strips effectively once delamination occurred. In the end, the CFRP U-Wraps delaminated immediately after the CFRP strips delaminated. Then for specimen 3, with the addition of the CFRP anchors only, the CFRP strips were effectively held in place even after delamination occurred. The only issue was around the CFRP anchor hole due to the concrete cover crushing before the CFRP strips reached their ultimate tensile capacity. Finally in specimen 4, the CFRP U-wraps were applied before the CFRP anchors to prevent the concrete from crushing. Due to this new anchorage scheme, the full tensile capacity of the CFRP strip was reach and only material failure of the CFRP strip was observed.

Based on the Load-Displacement curves for each specimen shown in Figure 5(b), adding additional anchorage increased both the strength and the ultimate displacement. The only specimen that was able to reach the target load was specimen 4, which reached 14.49 kN. This implies that based on the target performance required by the CFRP system, the inclusion of not only FRP anchors, but also U-Wraps may be necessary for proper detailing and strength capacity.

As previously mentioned, the most desirable failure mode involves the CFRP strip fracturing after the full tensile capacity is developed. Based on the failure modes of the specimens: delamination of the CFRP sheet (specimen 1 and 2), concrete failure around the anchor holes (specimen 3), and fracture of the CFRP sheets (specimen 4); it is clear that only specimen 4 resulted in the desired behaviour. This ultimately means that the inclusion of both the anchorage types is necessary for both detail and design, but further testing is required to determine a proper design criterion for the use of FRP anchors to help mitigate progressive collapse.

## 6 **CONCLUSIONS**

Throughout the years, there has been a wide variety of not only testing but application of FRP anchors. This paper was able to provide a brief glimpse into the recent successful testing of FRP anchors.

From the first case study, which investigated repairing damaged RC columns, it was determined that by just generically looking at the force-displacement responses, it is clear that the repaired column outperformed the original column. Ultimately the repair system was able to delay the rupture of the longitudinal reinforcement. Furthermore, the anchorage was successful in relocating the plastic hinge location as desired. Also, it was observed that at the early ductility levels, the additional anchorage allowed the base of the column to remain elastic while the column began to rotate about the newly located plastic hinge region.

While investigations into strengthening bridge beams for shear found that additional CFRP anchorage can increase the shear strength by 50%. The CFRP anchors were also able to change the failure type of the CFRP strips from debonding failure to fracture of the strips at beam failure. In the end, the use of the CFRP anchors allows for the rehabilitation of CFRP to become a more reliable system because failure by rupture is more predictable then failure by debonding to the concrete substrate.

Looking specifically at rehabilitated RC shear walls, each wall showed an improved flexural behaviour at the 6th story level and reduced the wall's rotation by 28% and 22% for the first and second wall, respectively. For both walls, the maximum inter-story drift ratio decreased at the 6th story, but there was no significant effect on the maximum roof drift. When comparing the two tested anchor details, the detail used in W1 is recommended over W2. However, if anchor detail from W2 is desired, the detail of the CFRP anchor should be in such a way that the direction parallel to its axis elongates without any undesired outward deformation, which uses part of the longitudinal strains.

Finally, when applying CFRP for progressive collapse prevention, it is necessary to incorporate both CFRP anchors and CFRP U-wraps into the design. This allows the CFRP strip to reach its full tensile capacity. However, if only the CFRP anchor or the CFRP U-wraps are used individually, there is a possibility of premature failure of the CFRP strip, which leads to failure of the CFRP anchor or the CFRP U-wrap.

Even with all this plethora of testing, there is still research that needs to be conducted. This includes the continued testing of the transition slope between connecting elements, which was mentioned in the research conducted by both the Concordia University and University of Texas at Austin. Not only this but accurate design guidelines for incorporating various geometries and configurations of CFRP anchors and CFRP U-wraps. Ultimately, the research is constantly evolving and there is brewing excitement when the next phase of testing begins.

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