Repair of Damaged Circular Reinforced Concrete Columns By Plastic Hinge Relocation

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SUMMARY:
This paper describes a new repair technique that involves the use of plastic hinge relocation to restore strength and deformation capacity of reinforced concrete bridge columns. Summarized is the overall repair concept and experimental results which include the reversed cyclic testing of 3 large-scale bridge columns that were previously damaged, repaired using the proposed methodology, and then subsequently retested. To-date, two different repair alternatives were executed, utilizing unidirectional carbon fiber sheets in the hoop and longitudinal directions; the latter anchored into the RC footing with 30 mm diameter carbon fiber anchors. The responses show that the proposed hinge relocation technique is able to restore the lost strength and displacement capacity of damaged RC columns.

Keywords: hinge relocation, reversed-cyclic loading, CFRP repair, damaged RC columns

1. INTRODUCTION

Modern seismic design practices for bridge structures involve the use of capacity design principles that locate plastic hinges in columns, while protecting against other modes of failure or locations of damage (Paulay and Priestley, 1992; Priestley, Seible, and Calvi, 1996). For large earthquakes, the formation of plastic hinges in columns can lead to buckling and rupture of longitudinal steel, such as that shown in Fig. 1.1. Traditionally, once incipient buckling occurs, bridge columns are generally replaced as the cost to replace portions of bars can be prohibitive. Replacement is deemed necessary since the inelastic strain capacity of reinforcing bars is severely diminished once buckling occurs, rendering the structure vulnerable to collapse in the next seismic event.

Figure 1.1. Buckled longitudinal reinforcement

Past research on column retrofit has focused on issues related to deficiencies in shear, lap splices, or confinement. Numerous techniques have been developed for column retrofit including, steel, concrete or advanced composite jackets (Priestley, Seible, and Calvi 1996). These retrofit techniques can also be utilized to repair columns with deficiencies exposed during seismic loading, or to repair well designed columns that have formed mild plastic hinges (without any signs of bar buckling). However, once buckled or ruptured bars are observed it is assumed that repair is no longer feasible. It is the objective of this paper to challenge this assumption via relocation of the plastic hinge to a position slightly higher in the column that remained essentially elastic during the initial seismic attack. In order to accomplish this objective, it will be essential to increase the flexural strength of the original plastic hinge by a large enough amount to force the secondary plastic hinge, which may form during the next seismic event, further up the column. This is accomplished in this research through the use of carbon fiber sheets, which are oriented in the vertical and transverse directions and externally bonded to the surface of the column in the previous plastic hinge region. The vertical carbon fiber sheets are then developed utilizing carbon fiber anchors embedded into the column footing. While this could also be done with conventional materials such as steel dowels, the targeted use of carbon fiber anchors allows for a rapid and durable repair solution.

2. DESIGN PHILOSOPHY AND EXPERIMENTAL STUDIES

2.1. Methodology

The basic philosophy of hinge relocation in reinforced concrete bridge columns for new design was first proposed by Hose et al. (1997). In their work, they successfully relocated the hinge away from the footing interface by providing additional steel in the plastic hinge region, thus forcing the hinge upwards. For repair, this concept is revisited as shown in Fig. 2.1.

The first step involves selection of the location of the new hinge. For this research, this was chosen as 400 mm above the base as the reinforcing bar strain at this location was significantly lower than the region below this height with peak strains reaching 0.005 in compression and 0.03 in tension. While further distances from the footing are possible, it is important to note that the further the hinge is relocated, the greater the rotation demands will be on the new hinge to reach the same lateral deformation capacity. Furthermore, the level of strengthening needed in the original plastic hinge increases as the distance to the new plastic hinge increases, making repair more difficult while also imparting higher moment into the footing. Therefore, the hinge should be relocated the minimum amount necessary for good seismic performance.

The second step involves extrapolation of the moment capacity of the section at the new hinge location to the base. After application of an overstrength factor of 5%, this allows for determination of the required moment capacity for the section at the base, as seen in Eqn. 2.1. The final step involves the design of the strengthened section, which will be discussed in detail later.

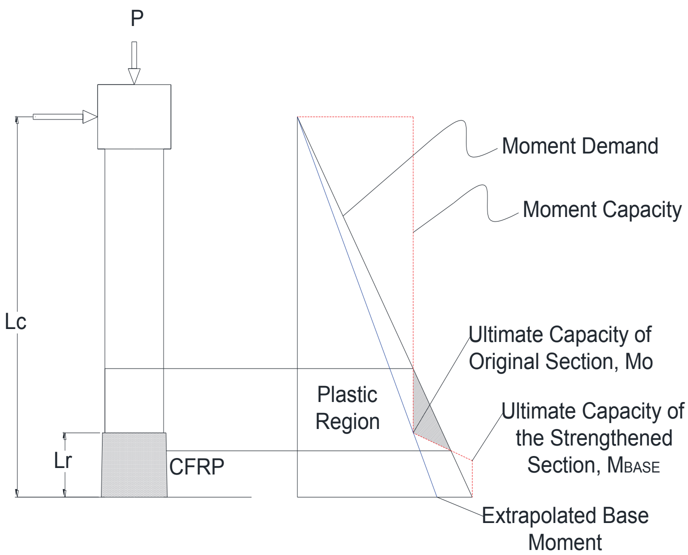

Figure 2.1. Moment demand versus moment distribution

$$M_{BASE} = 1.05\left(\frac{M_O L_C}{(L_C - L_r)}\right) \tag{2.1}$$

2.2 Test specimens and material properties

In order to study the proposed repair methodology, a series of 3 large scale tests were conducted. The specimens used in these tests represent a single degree of freedom bridge column. The columns are 2.4 m high and 600 mm in diameter containing 16 #6 (d_b = 19 mm) ASTM A706 longitudinal reinforcing bars and #3 (d_b = 9.5 mm) ASTM A706 spiral reinforcement with a 50 mm pitch as shown in Fig. 2.2. The repair to relocate the plastic hinge utilized CFRP sheets and carbon fiber anchors as will be discussed later. The material properties used in design of the repair and the RC columns are given in Table 2.1 where the CFRP sheet and carbon fiber anchor material properties are those of the gross composite.

The columns were subjected to real earthquake load histories prior to repair, and each reached different, but similar, peak tensile strains and displacement ductility levels as summarized in Table 2.2. Each of the columns contained buckled longitudinal reinforcement after the initial earthquake load histories, with one column containing ruptured longitudinal bars as can also be seen in Table 2.2. As previously noted, the repair systems were designed to relocate the plastic hinge to a location higher in the column where the longitudinal reinforcement has a much higher strain capacity relative to that at the original hinge location near the base of the column.

Three columns were repaired with the goal of relocating the plastic hinge. The first column, which contained buckled, but not fractured reinforcement, was repaired to increase the flexural strength of the original hinge, while also providing additional confinement to the new hinge location. The second column, which also contained only buckled reinforcement and no ruptured bars, was repaired to increase the flexural strength of the original hinge without attempting to increase the ductility of the new hinge. The third column, which contained buckled and fractured bars, was repaired in the manner similar to the second column.

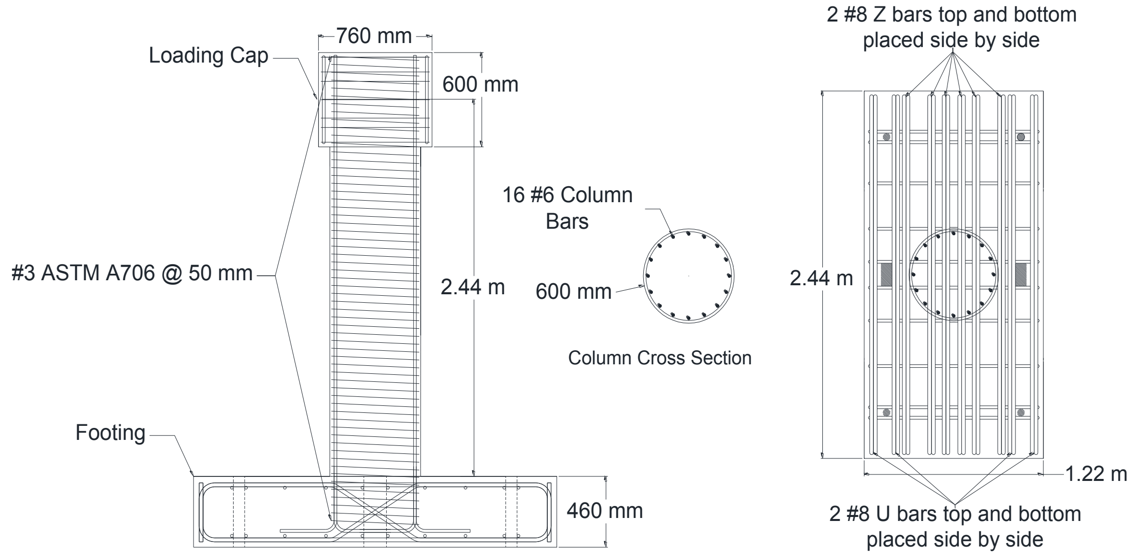

Figure 2.2. Column specimen reinforcement details

Table 2.1. Material properties

Longitudinal Steel		Transverse steel	Concrete	Composite CFRP Sheets		CFRP Anchors	
Yield	Max	Yield	f'_c	Tensile Strength	Tensile Modulus	Tensile Strength	Tensile Modulus
469 MPa	654 MPa	511 MPa	42.1 MPa	834 MPa	82 GPa	745 MPa	61.5 GPa

Table 2.2. Previous load history effects

Specimen	1	2	2	3
Load History	Kobe 1995	Chile 2010	Cyclic Aftershock	Chichi
Peak Displacement	210 mm	184 mm	169 mm	188 mm
Displacement Ductility	10	8.7	8	8.9
Peak Tensile Strain	0.059	0.051	0.048	0.052
Buckled Bars	2	2		2
Ruptured Bars	0	0		3

2.3. Repair design philosophy

The design philosophy of the repair for the three columns was to relocate the plastic hinge to a higher location in the column, yet still achieve the same displacement capacity and strength as the original undamaged column. As previously noted, the hinge was relocated to 400 mm above the base of the column, because at this location the longitudinal reinforcement experienced much smaller strains as compared to the region in the bottom 400 mm of the column height. In order to force the plastic hinge to this location, the base of the column was strengthened with vertical CFRP reinforcement anchored into the footing. The use of CFRP in this manner is appropriate as this strengthened original hinge is designed to remain elastic after the repair. In accordance with capacity design principles, it becomes a 'capacity protected location', with the plastic hinge forming in a section that contains only longitudinal steel for moment strength. For the vertical fibers to develop their full capacity at 400 mm above the footing, a development length of 200 mm was provided for the vertical fibers above the 400 mm location, with the carbon fiber anchors developing the vertical fibers from the base of the column. Conveniently, the CFRP sheets were 600 mm wide, allowing for fibers in the hoop direction to cover the inner layers of vertical fiber and the splayed anchor fans, starting from the base of the column, which will be discussed in further detail later.

Due to this repaired and strengthened elastic region at the base of the column, a higher curvature is therefore required by the column section at the new plastic hinge location to achieve the same displacement at the top of the column as the original column. As a consequence, it was felt that additional confinement should be provided to the new hinge location to allow for the expected increase in curvature for the first test. Therefore, the design process began by conducting a moment-curvature analysis of the column incorporating a confinement model that considers the effect of both the internal steel spiral and the external CFRP hoop reinforcement (Hu. 2011). It was found that 6 layers of CFRP in the hoop direction were needed to achieve the required curvature. Therefore, 6 layers of hoop reinforcement were applied from the base of the column up to 1200 mm for the first test specimen. A moment-curvature analysis was then conducted to design the number of layers of CFRP sheets in the vertical direction in the bottom 400 mm of the column to ensure that the moment capacity at the new plastic hinge location could be reached corresponding to the curvature required to achieve the same column displacement as in the original column. This moment-curvature analysis assumed that the vertical fibers carried no force in compression, and used cyclic stress-strain curves from OpenSees for the longitudinal steel reinforcing bars in order to represent the stress-strain characteristics based on their residual strain from the original test. It was determined that three layers of vertical fibers were required. The moment demand versus moment capacity used for the design of the repair system can be seen in Fig. 2.1. The repaired region of the column is overstrengthened so that the capacity exceeds the demand at this location, forcing the hinge to form at the intended critical location. It is important to note that for the second and third tests, no additional confinement in the 600 mm to 1200 mm region was provided as will be discussed later.

In order to develop the three layers of vertical fibers at the base of the column, anchors were needed to develop the vertical tension force at the column-footing interface. Carbon fiber anchors were designed to resist the total rupture force of the vertical fibers. A total of 12 - 30 mm diameter anchors were needed; six on either side of the column. These anchors were embedded into the footing 350 mm with an anchor fan length of 350 mm splayed on the column. The anchor design was based on work done by Kim and Smith (2010) on the pullout resistance of single FRP anchors which were significantly smaller than the anchors used in this work.

2.4. Repair procedure

The repair of the columns began by removing any loose concrete from the column and the footing. The concrete cross-section was then restored using a commercial cementitious patching system. No special attention was given to the buckled longitudinal steel reinforcing bars. A wet layup technique was used to apply the CFRP system to the columns where the fibers were first impregnated by the epoxy resin and then applied to the column.

A single layer of vertical fibers was first placed on the column from the base up to 600 mm around the circumference. The dry carbon fiber anchors were then impregnated with the same epoxy and inserted into evenly distributed holes that were 38 mm in diameter and 350 mm deep that were previously drilled into the footing. Fig. 2.3 shows the carbon fiber anchors prior to impregnation and Fig. 2.4 shows the insertion of the anchors into the footing. The anchor fans were then splayed onto the column. Two more layers of vertical fibers, 600 mm long, were then applied to the repair region sandwiching the anchor fans between the layers of vertical fibers. The final step was to wrap the repaired region with six individual CFRP sheets with fibers in the hoop direction, each with a 300 mm overlap. As mentioned earlier, for column one only, six layers of hoop fibers were also wrapped around the 600 mm to 1200 mm region of the column to confine the expected new plastic hinge region as discussed in Section 2.3.

Figure 2.3. CFRP anchor impregnation

Figure 2.4. CFRP anchor insertion into footing

2.5. Test setup and procedure

The columns were stressed to the lab strong floor through the footing and a hydraulic actuator applied a lateral load to the top of the column through the loading cap. For the axial load, a spreader beam was placed on top of the column with two bars running through it into the lab strong floor. These bars were tensioned by two hydraulic jacks on top of the spreader beam. The test setup can be seen in Fig. 2.5.

A displacement-controlled symmetric three cycle set load history was used for these specimens based on the original yield displacement of the undamaged column. The loading protocol consisted of single push and pull cycles to ¼ Fy, ½ Fy, ¾ Fy, and Fy followed by three cycles of μ_{1}, $\mu_{1.5}$, μ_{2}, μ_{3}, μ_{4}, μ_{6}, μ_{8}, μ_{10}, and μ_{12}.

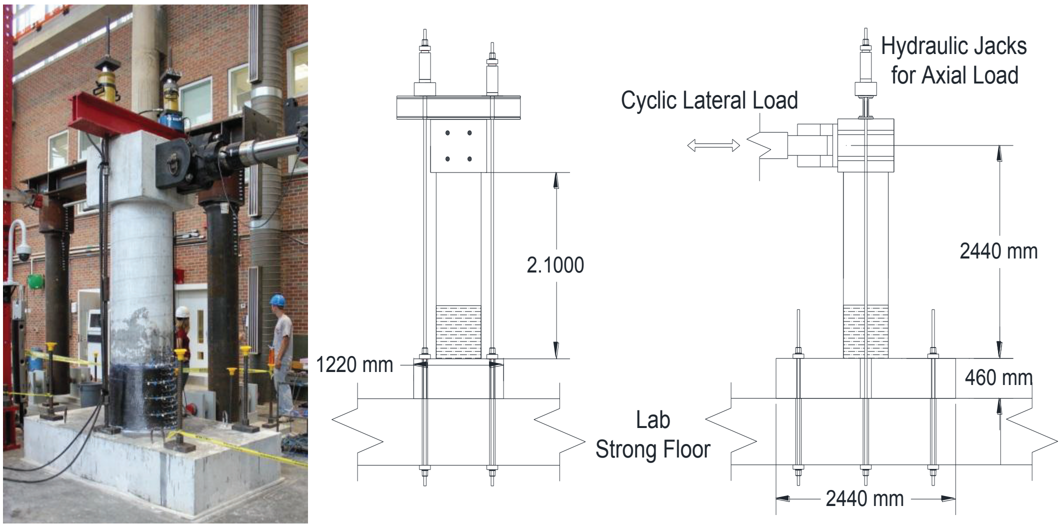

Figure 2.5. Column specimen test setup

3. RESULTS

During the research program that damaged the columns used in this investigation, column two was subjected to the Chile 2010 load history and then subjected to a three cycle set aftershock load history to induce buckling of the longitudinal reinforcement. This aftershock load history serves as the baseline for the comparison of the repaired columns, and its force-displacement response can be seen in Fig. 3.1 through Fig. 3.3.

The force-displacement response for the first repaired column is shown in Fig. 3.1. For this column, there is a 34% average increase in lateral force capacity compared to that of the aftershock study, as summarized in Table 3.1, which includes the peak conditions for all test specimens as well as a three cycle set performed on an undamaged column. While flexural cracking was visible in the region near 600 mm from the column base, the plastic hinge finally formed at a location just below the top of the footing. This is evidence that the confinement provided by the 6 layers of hoop reinforcement in the 600 mm to 1200 mm region of the column exceeded the predicted capacity, thus forcing the failure back into the footing. Consequently, the repair of column two was the same as that of one, except that no hoop fibers were provided for confinement of the 600 mm to 1200 mm region of the column. Fig. 3.2 shows the force-displacement response of repaired column two. Interestingly, a similar increase in strength was achieved and the plastic hinge was fully relocated to a location approximately 700 mm above the top of the footing, as seen in Fig. 3.4. It is important to note that the hinge formed at a higher location than the expected 400 mm from the base, which can be attributed to the efficient confinement of the original hinge location. The lack of additional hoop confinement in the higher location of the column, allowed the plastic hinge to fully form with ruptured and buckled longitudinal reinforcement above the level of the CFRP. Recall from Table 2.2 that the test three specimen contained three ruptured longitudinal bars on one side of the column. The demand on the carbon fiber anchors during testing proved too great, resulting in rupture of the anchors during testing. The force-displacement response for test three can be seen along with the aftershock response in Fig. 3.3. The same repair system that was used in test two was used for test three, due to the heavily congested footing, the anchor size and quantity of anchors could not be increased, therefore the same repair system was used. It is important to note that the repaired test three column experienced rupture of the CFRP anchors on both sides of the column. This is attributed to the increase in rotation at the base of the column after the initial rupture of the anchors on the side of the column containing the ruptured bars. It is thought that the compression cycles damaged the anchors, leading to rupture upon reversal. All of the repaired columns were able to exceed the force and displacement capacity of the original columns.

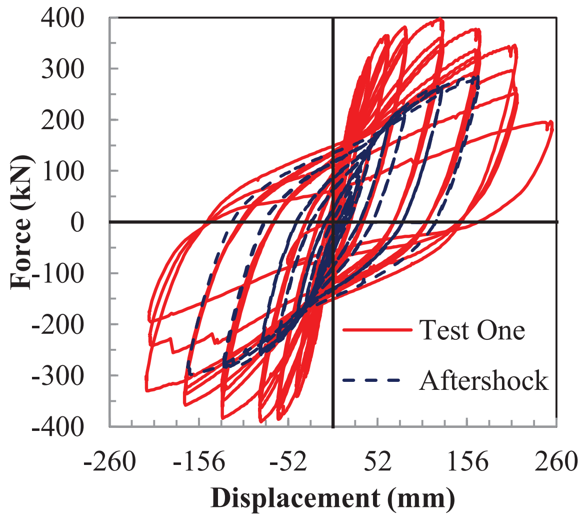

Figure 3.1. Test one response

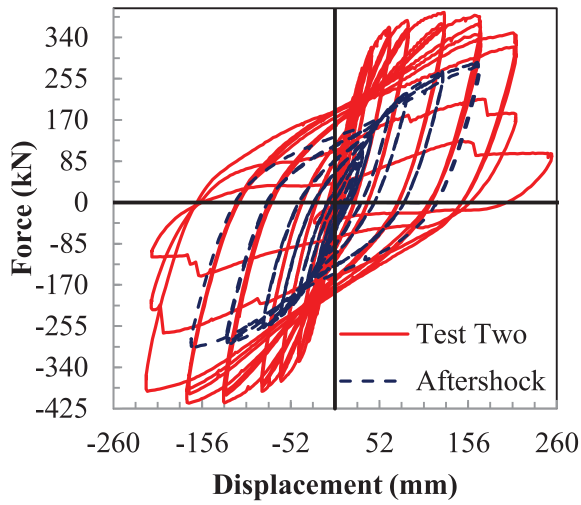

Figure 3.2. Test two response

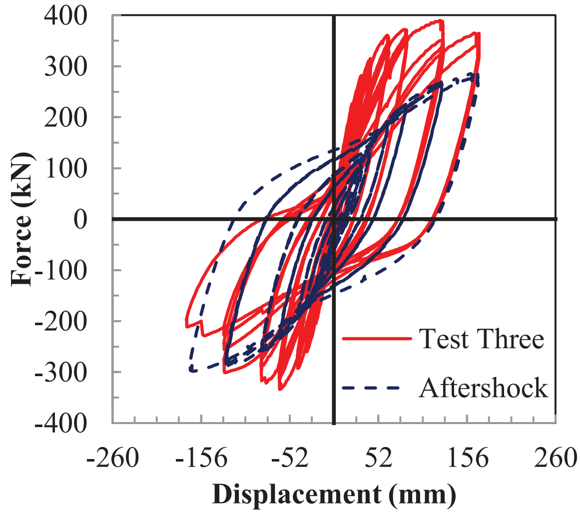

Figure 3.3. Test three response

For comparison, the force-displacement envelopes for the repaired columns and the aftershock column, as well as a three cycle set of an undamaged reference column, can be seen in Fig. 3.5. It can be seen that the repaired columns restored the initial stiffness up to the level of the original column, as well as increasing the displacement and force capacities.

Table 3.1. Peak specimen conditions

Test	Aftershock	Undamaged	One	Two	Three
Peak Applied Force, Push	284 kN	313 kN	391 kN	386 kN	389 kN
Ductility Level	8	6	6	6	6
Peak Applied Force, Pull	296 kN	308 kN	383 kN	411 kN	334 kN
Ductility Level	8	6	3	6	3
Peak Displacement	169 mm	216 mm	255 mm	254 mm	171 mm
Ductility Level	8	10	12	12	8
Component Failure	Rebar	Rebar	Anchors	Rebar	Anchors

Figure 3.4. Peak Displacement: test one (left); test two (center); test three (right)

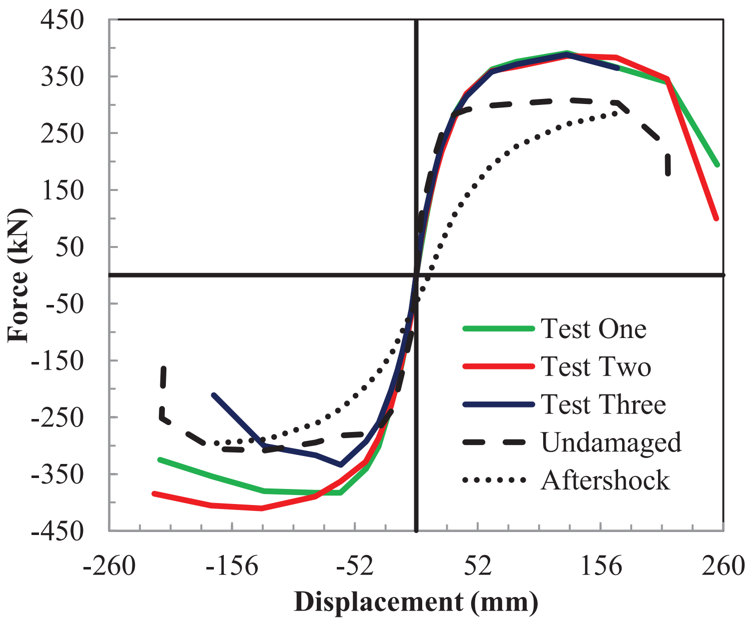

Figure 3.5. Force-displacement envelopes

4. FORCE-DISPLACEMENT PREDICTIONS

A reliable method for predicting the force-displacement response in a RC member subjected to single bending is the plastic hinge method, as presented by Priestley, Calvi and Kowalsky (2007). This method replaces the actual curvature distribution with an equivalent distribution of curvature that provides the same displacement as integrating the actual curvature distribution. This method is based on a plastic hinge length, L_p, over which the maximum strain and curvature from the base section of the column is considered to be constant. The plastic hinge length incorporates the strain penetration length, L_{sp}, which is a function of the yield stress and diameter of the longitudinal reinforcement. Above the plastic hinge region the curvature is considered to be linear, which is extrapolated from the yield curvature at the column base, as seen in Fig. 4.1.

The force-displacement responses for the repaired columns were found using a modified plastic hinge method. The curvature distribution in the modified method utilizes two plastic hinge locations, one just above the level of the repair system, or at the intended location, and one at the column-footing interface, as seen in Fig. 4.2. In this instance, two sections of the column must be analysed; the original column cross-section above the level of the repair system, and the strengthened section at the column-footing interface. Using the moment-curvature responses from these two cross-sections with the modified plastic hinge method, the force-displacement predictions for tests one through three can be seen in Fig. 4.3 through Fig. 4.5.

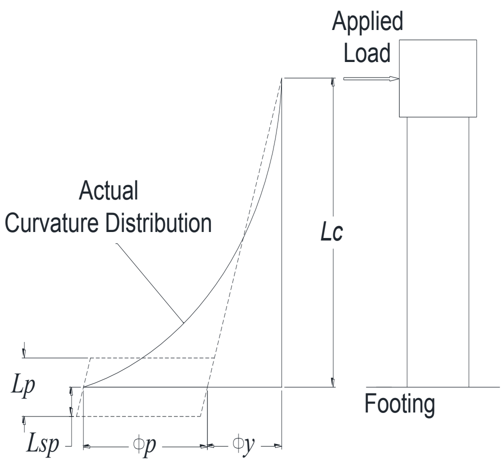

Figure 4.1. Plastic hinge method

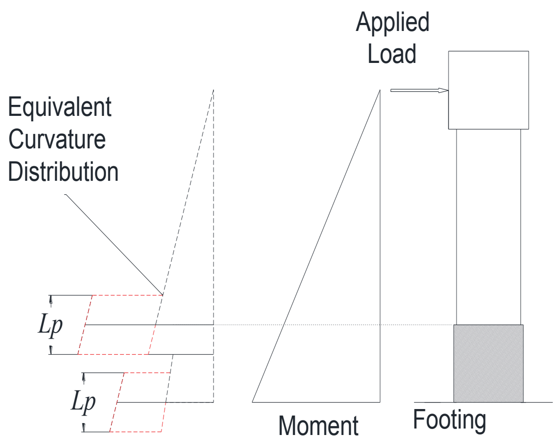

Figure 4.2. Modified plastic hinge method

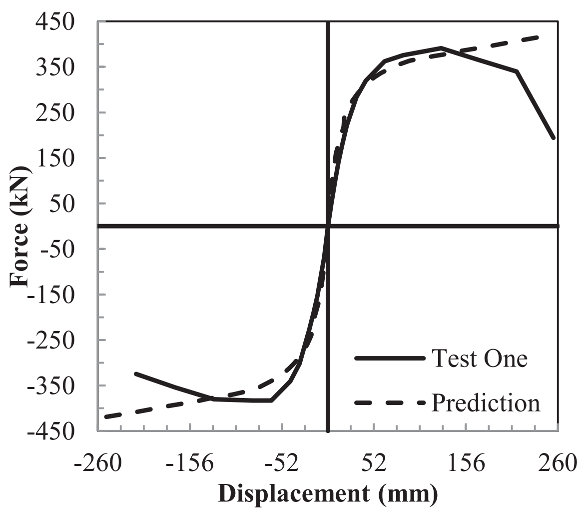

Figure 4.3. Test one prediction

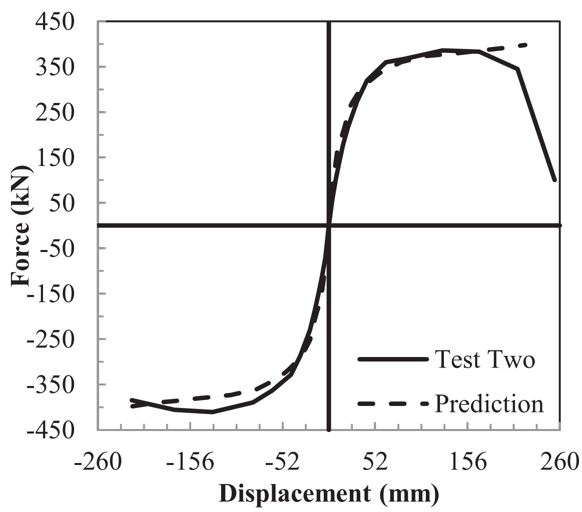

Figure 4.4. Test two prediction

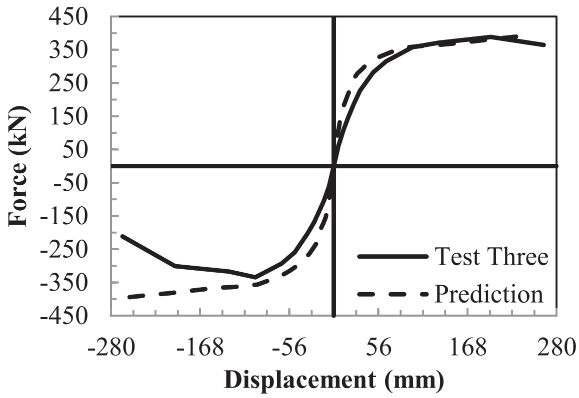

Figure 4.5. Test three prediction

It can be seen that the predicted responses for all three tests fit fairly well, with the test two prediction fitting the best. The force-displacement prediction analysis is based on the moment-curvature responses of the repaired section as well as the original column section just above the repair system. From these responses, the predictions assume that the failure of the column occurs above the level of the repair system, which was not the case for tests one and three, which resulted in rupture of the carbon fiber anchors at the base of the column. From these predictions it can be seen that the modified plastic hinge method yields accurate predictions when accurate moment-curvature responses are used.

5. CONCLUSIONS

This paper presents the results of a study on the repair of circular reinforced concrete bridge columns by plastic hinge relocation. While only a small number of tests have been conducted, the results are promising. By strengthening the base section of columns that contain buckled reinforcing bars with FRP anchors, it was possible to relocate the plastic hinge to a location in the column that sustained a much smaller degree of inelastic action during the original seismic loading. The proposed method has the advantage of quick installation, while retaining the benefit of ductile response of traditional reinforcing steel.

ACKNOWLEDGEMENT
The authors would like to thank the Alaska Department of Transportation and Alaska University Transportation Center that provided the funds for the initial construction of the test columns as part of a different research program and Fyfe Co. LLC for their support of this research through the NSF Industry/University Cooperative Research Center on Integrating Composites in Infrastructure (CICI), as well as the entire technical staff of the Constructed Facilities Laboratory at NCSU.

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