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SHEAR REPAIRED RC BEAM BY FRP BONDING WITH EXTERNAL POST-TENSIONING

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Various factors, including increase in traffic volume and weight, structural aging, and environmental impact, cause damage in structural members. This raises the importance of the maintenance, rehabilitation, and strengthening of reinforced concrete members. External post-tensioning is one of the widely-used strengthening techniques in many countries due to its advantages over other strengthening methods. Although flexural strengthening of existing structural members is a well-established method, shear strengthening of structural members, especially with existing shear cracks, has attained very little attention from researchers. Similarly, external fiber-reinforced polymer (FRP) bonding for shear strengthening of structural members, especially with existing shear cracks, is a relatively new area of research. This paper presents the results of an experimental study on the shear strengthening of reinforced concrete (RC) beams with existing shear cracks by external post-tensioning and external FRP bonding. The test result showed that the combined strengthening technique of external post-tensioning and external FRP bonding can effectively increase the shear capacity of RC beams with existing shear cracks.

Keywords: Fiber Reinforced Polymer (FRP), Reinforced Concrete, Shear strengthening, Shear cracks.

1 INTRODUCTION

Many existing structures around us need repair or retrofitting for various reasons, such as natural disaster, design using older codes and guidelines, construction defaults, increase in loading conditions, environmental degradation etc. Several strengthening techniques have been developed to repair damaged structural members. External post-tensioning is widely used all over the world to strengthen existing structures due to several advantages such as easier maintenance, cost effectiveness, ease of application etc. However, when external post-tensioning is used to strengthen shear damaged reinforced concrete members, unlike with flexural damage the efficiency is significantly reduced by existing shear cracks. Furthermore, the effect of existing shear cracks is a complex function that depends on a number of parameters, including crack width, crack inclination, shear reinforcement ratio, and concrete strength.

Due to such complexity, only a few researchers have investigated the behavior of shear cracks and its effect on the capacity of reinforced concrete (RC) beams. Aravinthan and Suntharavadivel (2007) studied the effect of existing shear cracks on the shear capacity of bridge bent caps strengthened by external post-tensioning. They investigated six bent caps scaled models of two different bridges. Asymmetric loading was applied to simulate the loading from the main girder of the actual bridge that caused cracks in the bent caps. It was concluded that existing shear cracks have substantial influence on RC member capacity. The member capacity can be increased up to 70% by external post-tensioning if the existing shear cracks are properly repaired.

The use of fiber-reinforced polymer (FRP) in structural application has become very popular in recent years because of its many advantages, such as high strength to weight ratio, ease of construction, non-corrosive characteristics, and reduced long-term maintenance cost. Recently studies on FRP used on RC beams have reported that shear capacity can also be increased by external FRP bonding (Al-Sulaimani et al. 1994, Hadi 2003, Adhikary and Mutsuyoshi 2004, Mosallam and Banerjee 2007, Jayaprakash et al. 2008, Obaidat et al. 2011). However, few studies have considered the effects of existing shear cracks on the shear capacity enhancement by external FRP bonding.

Al-Sulaimani et al. (1994) tested sixteen rectangular RC beam specimens strengthened with external glass-fiber-reinforced polymer (GFRP) plate bonding, which showed GFRP-bonding schemes can increase the shear capacity and stiffness of the shear damaged RC beam. Hadi (2003) studied sixteen shear-damaged RC beam specimens retrofitted with different amounts of GFRP and CFRP (carbon-fiber-reinforced polymer), showing that the FRP bonding technique can significantly increase the shear capacity of shear damaged RC beams, and the efficiency varies with parameters. Similar results also were reported by Mosallam and Banerjee (2007) based on their experiment on RC beams with external FRP bonding. Jayaprakash et al. (2008) used bi-directional CFRP strips to strengthen pre-cracked rectangular RC beams in shear, finding that the application of CFRP strips increased the shear capacity of the pre-cracked beams by up to 13%. Obaidat et al. (2011) investigated the behavior of structurally-damaged full-scale RC beams retrofitted with CFRP laminates, noting that shear retrofitting with externally-bonded CFRP plates increased the load bearing capacity as well as the stiffness of the beams.

As the literature indicates, the application of external post-tensioning and external FRP bonding can individually increase the shear strength of shear-damaged RC beams. The following study was conducted to investigate the efficiency of the combined strengthening technique by external-post tensioning and external-FRP bonding to improve the shear capacity of RC beam with existing shear cracks.

2 EXPERIMENTAL PROGRAM

2.1 Fabrication of Beam Specimens

Five RC beams were made for the experimental program using the laboratory facility within the Concrete and Structures Lab at the Central Queensland University. The beam specimens were 2500 mm long and had a rectangle cross section of 300 mm × 150 mm. Two 12 mm-diameter N-type (yield strength, f_{sy} = 500 MPa) bars at the top and two 16 mm-diameter N-type bars at bottom were used as the longitudinal flexural reinforcement. Six mm-diameter R-type (f_{sy} = 250 MPa) shear ligs were provided at a spacing of 150mm within the shear zone.

Two 25 mm-diameter Macalloy bars (failure load = 506 kN each) were used for the post-tensioning. The CFRP sheet used in the test was MBRACE CF 230/4900 with a modulus of elasticity of 230 GPa, average fiber thickness of 0.8 mm per layer, and an ultimate tensile strength of 4900 MPa.

2.2 Application of CFRP to the Concrete Surface

At first the surface was prepared as per the CFRP supplier's recommendations. The surface was cleaned to remove any impurities within the concrete surface. Primer was applied to the prepared concrete surface and, when the primer became tack-free, the saturant was applied to the primed concrete surface. The pre-cut CFRP strips were placed onto the concrete surface at the marked locations and pressed down. Figure 1 illustrates the layout of CFRP strips. All specimens were allowed to cure for at least seven days in an enclosed environment.

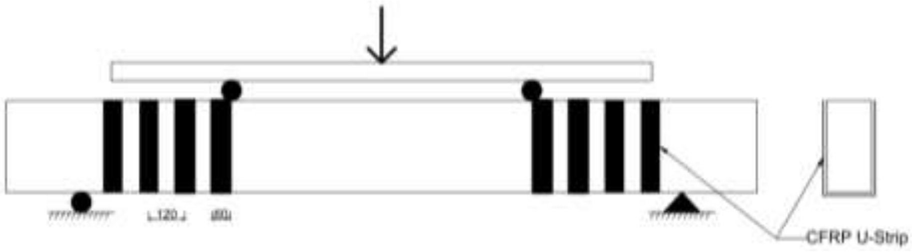

Figure 1. The CFRP layout used for strengthening the beam specimens.

2.3 Instrumentation and Experimental Set-up

Figure 2 shows the test setup during the final testing procedure. The post-tensioning was applied with eccentricity of 50mm from the center of the beam. Linear Variable Differential Transformer (LVDT) was used to measure vertical deflections of the tested beam specimens at the midpoint location along the beam length.

Figure 2. The test set-up.

2.4 Experimental Procedure

A four-point loading at a rate of 2 mm/min was applied for all five beam specimens. For the control beam the loading was applied until the beam failed and the corresponding loading was recorded. Three other beam specimens were pre-loaded until first sign of visible shear cracks. The last beam was kept to be undamaged for external strengthening. All beams except the control beam were strengthened with external CFRP U-strips; three beams with two layers of CFRP and one beam with one layer of CFRP. The repaired beams were then post-tensioned with an initial prestressing force of 100 kN. Then the beams were loaded until they failed.

3 RESULTS AND DISCUSSIONS

The control beam failed in shear as expected and the ultimate load at failure was 288 kN. At a 140 kN load, the shear cracks were fully developed starting from near the left support, propagating diagonally towards the left loading point. At the ultimate load, the beam failed in shear with large cracks opening on the left side of the beam.

Beam 2 was pre-loaded up to 228 kN vertical load until the appearance of the first shear crack and then the damaged beam was strengthened with two layers of CFRP U-strips. The beam was then tested under the same test set-up but with the addition of the 100 kN external horizontal post-tensioning. The beam failed by debonding of the CFRP strips, followed by concrete shear failure, as can be seen in Figures 3 and 4. The failure load for this beam specimen was 431.3 kN, which was 49.7% higher than the failure load of the control beam. The ultimate deflection at the midpoint of the beam specimen was 26.93 mm.

Figure 3. Failed beam specimen.

Figure 4. CFRP delamination and shear failure of beam specimen.

Beam 3 was pre-loaded up to 215 kN, then strengthened with two layers of CFRP U-strips and post-tensioned. This beam also failed by CFRP strips debonding, followed by concrete shear failure. The failure load was 372.5 kN, which was 29.4% higher than the control beam's failure load; the ultimate midpoint deflection recorded was 27.59 mm.

Beam 4 was pre-loaded up to 235 kN and repaired with one layer of CFRP U-strips. Vertical loading was applied along with the horizontal post-tensioning. The beam failed at 399.7 kN in a similar failure mode as before, and the failure load was 38.8% higher compared to the control beam. The ultimate midpoint deflection was 28.45 mm.

Beam 5 was shear strengthened with two layers of CFRP U-strips, and post-tensioned before the load was applied. The beam failed in shear after the CFRP strips debonded from the concrete surface. The ultimate load at failure was 430.4 kN, which was 49.5% higher than that of the control beam. The ultimate midpoint deflection was 31.09 mm.

Table 1 summarizes the test results. Figures 5 and 6 illustrate the load deflection diagrams for the tested beam specimens. The behavior of the CFRP strengthened beams can be clearly seen in the figures.

Table 1. Test results.

Beam No	**Description**	**Concrete Strength (MPa)**	**Ultimate Load (kN)**	**Ultimate Deflection (mm)**	**Failure Mode**
1	Control Beam	25.1	288.0	-	Shear
2	Pre-cracked, 2 layers of CFRP	25.8	431.3	26.93	Shear-CFRP delamination
3	Pre-cracked, 2 layers of CFRP	25.8	372.5	27.59	Shear-CFRP delamination
4	Pre-cracked, 1 layers of CFRP	24.7	399.7	28.45	Shear-CFRP delamination
5	No Pre-cracking, 2 layers of CFRP	25.9	430.4	31.09	Shear-CFRP delamination

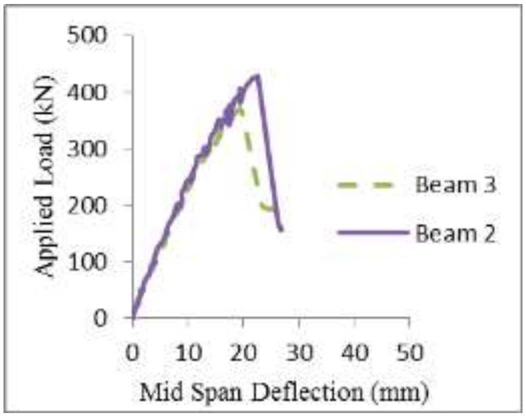

Figure 5. Load-deflection diagram for Beam 2 and Beam 3.

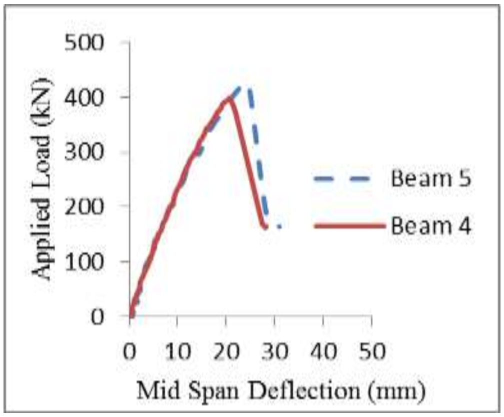

Figure 6. Load-deflection diagram for Beam 4 and Beam 5.

4 CONCLUSION

This experiment investigated the efficiency of the external CFRP bonding together with post-tensioning in increasing the shear capacity of shear damaged RC beams. From the experimental results, it was found that the combined strengthening technique of external horizontal post-tensioning and CFRP-strips bonding can effectively increase the shear capacity of shear damaged RC beams. Delamination of the CFRP strips initiated the failure of all the strengthened beams, suggesting even a higher shear capacity can be achieved by preventing delamination. The shear capacity gain by damaged RC beams strengthened using this strengthening technique may vary depending on the initial crack pattern and crack width. Further investigation should be carried out to better understand and improve the efficiency of this combined strengthening scheme.

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