Shear Strengthening of Cracked RC Beam Using External Post-tensioning

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ABSTRACT: Currently many bridges are considered inadequate for the current traffic loads due to various problems including rapid increases in the traffic volume and vehicle loads; exposure to adverse environmental conditions and structural aging. These bridges require either weight restriction, strengthening or even total replacement. Strengthening of such bridges is cost-effective for bridge engineers rather than total replacement. External post-tensioning is considered as one of the effective methods to strengthen bridge structures. Unlike flexural strengthening, the shear strengthening of existing structures using external post-tensioning has not been investigated adequately. The existing shear cracks may have substantial effect in shear strengthening of structural members using conventional external post-tensioning. Even most of the current design codes do not have provision for the existing shear cracks (except some guidelines recommend these cracks should be repaired prior to strengthening). This paper presents an experimental investigation on the effect of the existing shear cracks in such members strengthened with external post-tensioning.

1 INTRODUCTION

Generally reinforced concrete members are designed to fail in flexural mode under ultimate loading conditions. Therefore, most of the studies have focused on the flexural strengthening of reinforced concrete members. However, some structural members such as bridge headstocks (also known as bent-caps) need to be strengthened for both flexure and shear due to the type of loading. The failure of the headstocks of Tenthill Creek Bridge (Australia) and Hawthorne and Morrison Bridges (United States of America) are typical examples of shear failure of headstocks in bridges. Therefore, it is important to investigate the shear strengthening of concrete structures such as bridge headstocks.

External post-tensioning is one of the widely used strengthening techniques due to its advantages. Some of the advantages include:

- Economical construction;
- Easy monitoring and maintenance;
- Easy tendon placement and concreting;
- Wide range of usage in bridges.

External post-tensioning refers to a prestressing technique where the tendons are placed outside the concrete section. Strengthening of existing bridges using external post-tensioning is quite different to the construction of new bridges using external post-tensioning. Many factors influence the efficiency of the strengthening of existing bridges, the main one being the effect of existing cracks. These effects need to be fully investigated to achieve an optimum strengthening technique using external post-tensioning.

The flexural behaviour of new and existing bridge members by external post-tensioning has been studied in detail by many researchers (Aravinthan, Sabonchy & Heldt 2004; Daly & Woodward 1997; Harajli 1993; Niu 2000). However, there have been relatively limited investigations on the shear strengthening and the effect of shear in externally post-tensioned members (Tan & Ng 1998).

From the previous studies on flexural strengthening (Aravinthan, Sabonchy & Heldt 2004; Harajli 1993), it is proven that the flexural cracks were almost or completely closed by the application of external post-tensioning. Hence, they have no influence on the capacity of the concrete beams. While a number of experimental studies attempted to study the effect of existing shear cracks in the reinforced concrete members (Khaloo 2000; Teng et al. 1996), to the best of authors' knowledge, the effect of the existing shear cracks in externally post-tensioned member has not been investigated adequately.

This paper presents the experimental investigation on the effect of existing shear cracks in the concrete member strengthened by external post-tensioning. In addition, the efficiency of the epoxy injection for the crack repair is discussed, which is a recommended repair technique (American Concrete

Institute 2003; FIP Commission on Practical Construction 1991).

2 EXPERIMENTAL METHODOLOGY

The experimental program consisted of four reinforced concrete beams with rectangular cross section of 300x150 *mm*. Each beam is 2500 *mm* long. Two N24 tensile reinforcements and two N16 compression reinforcements were placed. R6 bars were provided at 250 *mm* spacing in the shear span and at 100 *mm* near to the ends to support the external post-tensioning. Figure 1a shows the typical reinforcement layout of the experimental models. The effective span of the beam was set 2000 *mm*. Four-point loading was applied with the shear span 750 *mm* (Figure 1b).

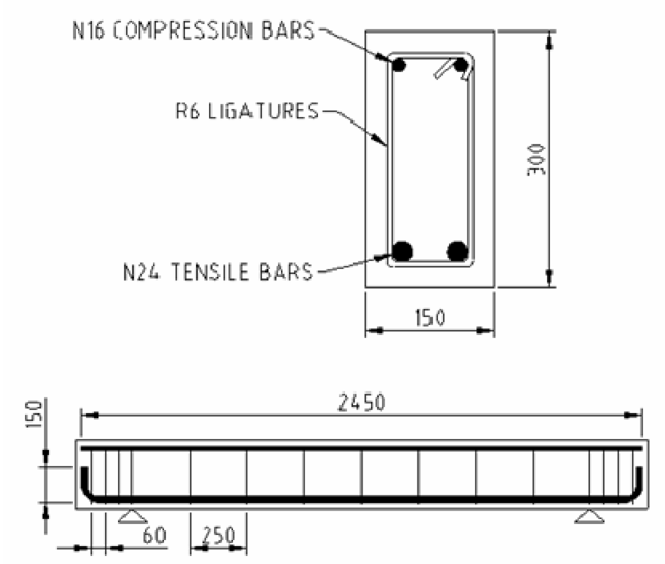

Figure 1a. Typical reinforcement layout of the beam

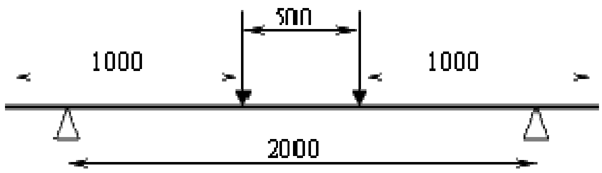

Figure 1b. Typical loading arrangement for the beam

Concrete strength is an important parameter in the testing of reinforced concrete beams and can significantly affect the test results, especially when estimating the shear strength. It was noted in a previous investigation by Alam that the specimens showed inconsistence results when the concrete strength varying between specimens (Alam 2004). Therefore, in the experimental program all four beams were prepared at the same time to make sure that the concrete strength was nearly the same. The specimens were cured under the same conditions to reduce the variation in concrete strength.

The first specimen RCB1 served as control beam and tested under static loading without any strengthening. The second beam, RCB2, was pre-loaded to cracking and later strengthened by external post-tensioning and reloaded until the failure. The third specimen, RCB3, was also pre-loaded to cracking and these cracked were repaired using epoxy injection as shown in Figure 2. Then RCB3 was strengthened by external post-tensioning and loaded again until failure. The last beam, RCB4, was strengthened by external post-tensioning and tested under static loading. This simulated the condition of a new beam with external prestressing. The test variables are summarised in Table. 1.

Figure 2. Repaired shear crack using epoxy injection

Table 1. Test variables of the experimental program

Specimen	Preloading	Epoxy Repair	Strengthening
RCB1	-	-	-
RCB2	√	-	√
RCB3	√	√	√
RCB4	-	-	√

For the strengthening purpose two 16 *mm* high tensile bars were used. Totally, 150 *kN* force was applied through the external rods (about 75 *kN* in each). Figures 3a and 3b show the typical experimental setup the control beam and post-tensioned beams.

Figure 3a. Experimental setup for the control beam

Figure 3b. Experimental setup for the post-tensioned beam

3 RESULTS AND DISCUSSION

3.1 *Member capacity*

Initially, some flexural cracks were observed in bottom of mid span section in the control beam, RCB1. However, they did not develop further as the load was increased. The first shear crack appeared at 125 *kN* near the tension side at the support and progressed with further loading. The control beam could achieve 196 *kN* before it failed in shear. The load-deflection of RCB1 is shown in Figure 4. The formation of shear cracks reduced its stiffness, which is noticeable in the figure. The maximum crack width at failure was 2.5 *mm* (Figure 5).

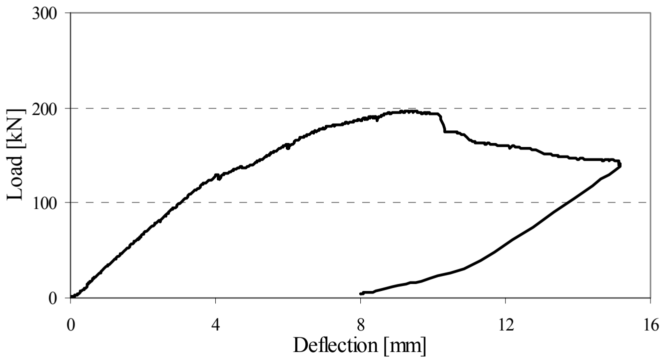

Figure 4. Load – Deflection curve of the control beam, RCB1

Figure 5. Failure of the control beam, RCB1

The second beam, RCB2, was initially loaded up to 90% of its capacity (about 180 *kN*) to simulate the initial cracks. The formation of cracks and its performance were very similar with RCB1. Then load was released for strengthening. After applying 152 *kN* prestress using external rods, the specimen was reloaded until failure. Even though high prestress was applied, the initial shear cracks were not fully closed with the application of external post-tensioning. The same cracks further widened and led to the failure during the second stage of loading, as shown in Figure 6. The failure occurred at 194 *kN*, slightly lower than the load on control beam. The load-deflection curve of RCB2 is shown in Figure 7. At the maximum load, the crack width was found to be 3 *mm* and it further increased to 8 *mm* at failure.

Figure 6. Failure of the control beam, RCB2

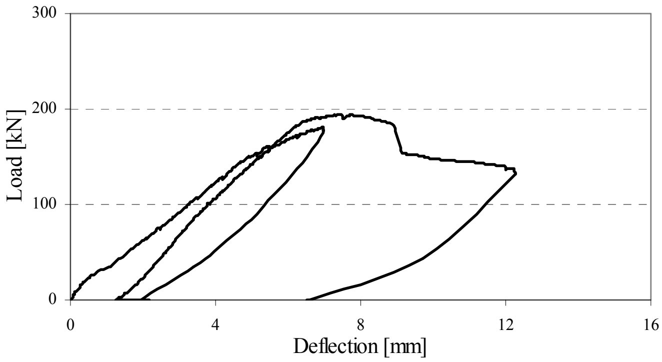

Figure 7. Load – Deflection curve of the control beam, RCB2

The third specimen RCB3 was loaded the same way as RCB2 and observed similar progress in initial crack propagation. The cracks were repaired with epoxy injection and allowed for a week to cure the resin and to develop a good bond. Then the specimen was prestressed to 150 *kN*, similar to RCB2, and reloaded. An interesting result was observed in the crack propagation. A new shear crack was initiated that lead to failure of the beam (Figure 8). The repaired crack did not open-up again during the subsequent loading. This proved that the epoxy repair was properly done. Furthermore, it has increased the capacity of the member to 310 *kN*, 58%

increment of control beam. Brittle failure was observed in the specimen RCB3, which is also different from the RCB2. The change of failure mode can be noticed in the load-deflection curve of the specimen RCB3 (Figure 9). At the maximum load, the crack width was found as 3 *mm* and it was 7 *mm* at failure.

Figure 8. Failure of the control beam, RCB3 (initial crack is highlighted)

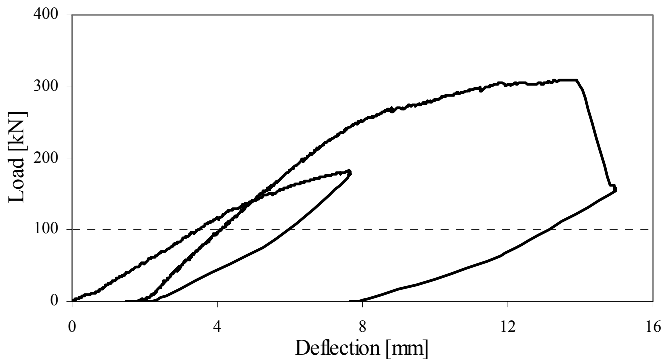

Figure 9. Load – Deflection curve of the control beam, RCB3

The last beam RCB4 was tested to obtain the effect of external post-tensioning in the uncracked reinforced concrete beam. The beam was strengthened with same prestressing force of 152 *kN* and tested under similar loading condition. The load-deflection behaviour of RCB4 is shown in Figure 10. The beam could achieve ultimate load of 354 *kN* before it failed in shear. The failure mode of RCB4 also was observed similar as RCB3.

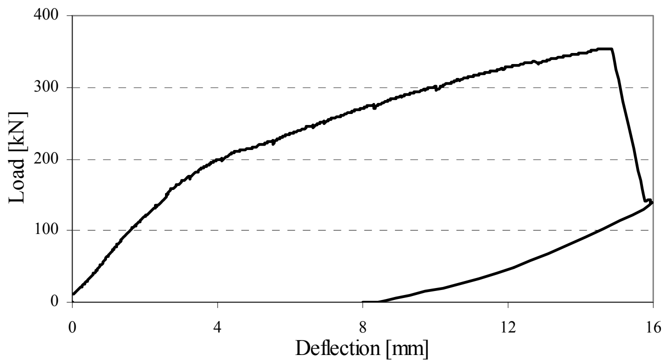

Figure 10. Load – Deflection curve of the control beam, RCB4

The ultimate load and dominant failure mode of each specimen are tabulated in Table 2. It clearly shows that, without repair shear crack can significantly reduce the efficiency of the strengthening by external post-tensioning. The properly repaired and post-tensioned beam had similar behaviour with the uncracked beam with post-tensioning.

Table 2. Summary of experimental program

Specimen	f'_c (*MPa*)	Ultimate load (*kN*)	Increase in Ultimate load (%)
RCB1	39.9	196	-
RCB2	40.3	194	-1
RCB3	40.4	310	58
RCB4	40.4	354	81

3.2 *Changes in prestressing force*

The applied prestressing force also increased as beams were loaded. The variation of the external prestressing force is shown in Figure 11.

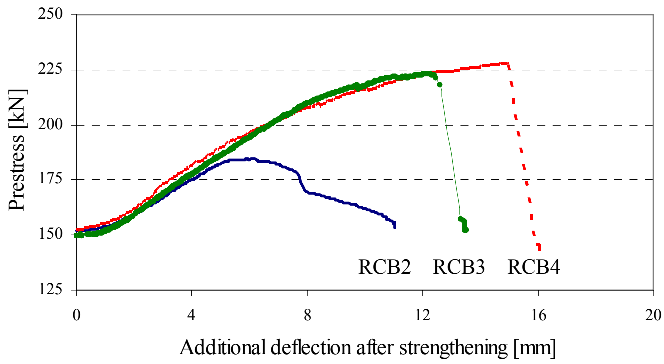

Figure 11. Increase in external prestressing force with deflection of the beams

It can be noted that the post-tensioned force in Specimens RCB3 and RCB4 has increased dramatically more than Specimen RCB2. This means that the tension side of the RCB2 has not increased in length as much as for RCB3 and RCB4. The reason is simple, the deflection has occurred in RCB2 due to the crack width increasing, not the beam bending as a whole. This further proved the effect of the existing shear cracks in the beam when it strengthened by external post-tensioning. When repaired properly by epoxy injection (RCB3), the behaviour is very much closed to the uncracked section. Once again, it proved that the behaviour of the beam can be improved by a proper repair of existing cracks prior to strengthening. Moreover, epoxy injection can be an effective repair technique for these kinds of structures. The increased values of prestress are summarised in Table 3.

Table 3. Changes in the prestressing force

Specimen	f'_c (*MPa*)	Prestress (*kN*)	
		Initial	Ultimate
RCB1	39.9	-	-
RCB2	40.3	152	184
RCB3	40.4	150	223
RCB4	40.4	152	228

3.3 *Effect of the existing shear crack*

From the experimental results it is clearly understood that the existing shear cracks have a substantial effect on the capacity of the reinforced concrete member strengthened by external post-tensioning. It is remarkably different from the effect of flexural cracks reported by previous researchers (Aravinthan, Sabonchy & Heldt 2004; Harajli 1993).

Unlike the flexural cracks which are nearly vertical, the shear cracks have an inclination of about 30^o–45^o to the horizontal. Therefore, the application of horizontal external prestressing is unlikely to close the shear cracks. In some cases, it may cause a negative effect in the shear capacity.

3.4 *Theoretical Predictions*

Current code of practice used in Australia does not give any provision to estimate the capacity of the cracked RC beams. Therefore, the comparison of the theoretical values is not possible at this stage. Further investigations are needed to develop a general equation to estimate the capacity of the cracked RC beams strengthened by external post-tensioning.

4 CONCLUSIONS

This paper presented the experimental investigation of the shear strengthening of reinforced concrete beams using external post-tensioning with existing shear cracks and possible repair techniques. Based on the experimental results, following conclusions can be drawn.

- Existing shear cracks have significant effect on the capacity of the reinforced concrete beam strengthened by external post-tensioning.
- Proper crack repair can reduce the effect of the existing crack and increase the member capacity up to 60%.
- Epoxy injection could be an effective technique for shear crack repair.
- Further investigation is needed on the effect of existing shear crack in a member strengthened by external post-tensioning.

The authors believed that the full investigation on the influence of the existing shear cracks on the efficiency of the strengthening of reinforced concrete members by external post-tensioning will lead more effective strengthening system of reinforced concrete structures.

5 ACKNOWLEDGEMENT

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