IS EXTERNAL POST-TENSIONING AN EFFECTIVE SOLUTION FOR SHEAR STRENGTHENING OF BRIDGE ELEMENTS?

Thiru Aravinthan
University of Southern Queensland
Faculty of Engineering and Surveying
Toowoomba QLD 4350
Australia
aravinthant@usq.edu.au

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ABSTRACT

Retrofitting of existing concrete structures has become an important issue nowadays in the construction industry. Such necessity had been caused by several factors, especially when concrete is subjected to severe environmental and loading conditions. In such situations, the remedy is either to demolish the existing structure and construct a new one or to retrofit the existing structure by an appropriate strengthening methodology. In this regard, external post-tensioning has been proven to be effective in flexural strengthening of bridge elements such as main girders, transverse girders and headstocks. There have been some attempts to use the external post-tensioning technology to increase the shear strength of bridge elements such as headstocks. One of the issues that need careful consideration is the presence of existing shear cracks in such structural elements. Recent experimental investigations using model specimens revealed that the strength enhancement by external prestressing is highly influenced by the existence of shear cracks in the concrete member. It was found that the external post-tensioning is only effective when the shear cracks are properly repaired by a suitable technique such as epoxy injection of cracks. This paper presents the results of the investigation, discussing the effectiveness of external post-tensioning in shear strengthening of concrete bridges, with a case study of Tenthill Creek Bridge in Queensland, Australia.

INTRODUCTION

External post tensioning is a common technique to increase the member capacity due to its relatively inexpensive materials and labour cost. Over the last two decades, many researchers have investigated the use of external prestressing for flexural strengthening of structural members such as girders (Harajli, 1993; Mutsuyoshi, Aravinthan & Hikimura, 1998; Tan & Tjandra, 2002). However, there has been only limited work on the shear strengthening of structural elements using external post-tensioning. Headstocks in existing bridges are some typical examples where shear strengthening may be required. When headstocks with large cracks need to be strengthened, one of the solutions for closure of such cracks is to provide a prestressing force by means of external post-tensioning.

To evaluate the effectiveness of external post-tensioning for shear strengthening, a series of experimental investigations were carried out using different shapes of headstocks. One of the test variables used in the model testing was the repair of existing shear cracks by epoxy injection technology. While it was generally believed that the external post-tensioning would increase the member capacity, the test results proved otherwise in the case of specimens that had existing cracks, but not repaired with epoxy injection. It was also observed that when the cracks were properly repaired, there was substantial increase in the shear capacity of the members. This paper describes the application of external post-tensioning for shear strengthening of headstocks using conventional prestressing techniques as well as the effect of existing shear cracks on strengthening by external post tensioning. This paper also discusses the application and the effect of epoxy injection as efficient repairing technique of the existing shear cracks. The repair and strengthening of the headstocks the Tenthill Creek Bridge is discussed as a case study including experimental results of the model test of the headstocks of this bridge.

PRELIMINARY EXPERIMENTAL INVESTIGATION ON SHEAR STRENGTHENING USING EXTERNAL POST-TENSIONING

The preliminary experimental program consisted of three reinforced concrete cantilever headstock specimens (PRCS1, PRCS2 and PRCS3) with rectangular cross section throughout its length of 2500 *mm*. All specimens were tapered shape cantilevers with cross section of 350x250 *mm* at the toe end and 400x250 *mm* at the heel end of the specimen. Fig. 1 shows the typical reinforcement layout of the specimen. Sufficient flexural reinforcement was provided to ensure flexural failure is dominant.

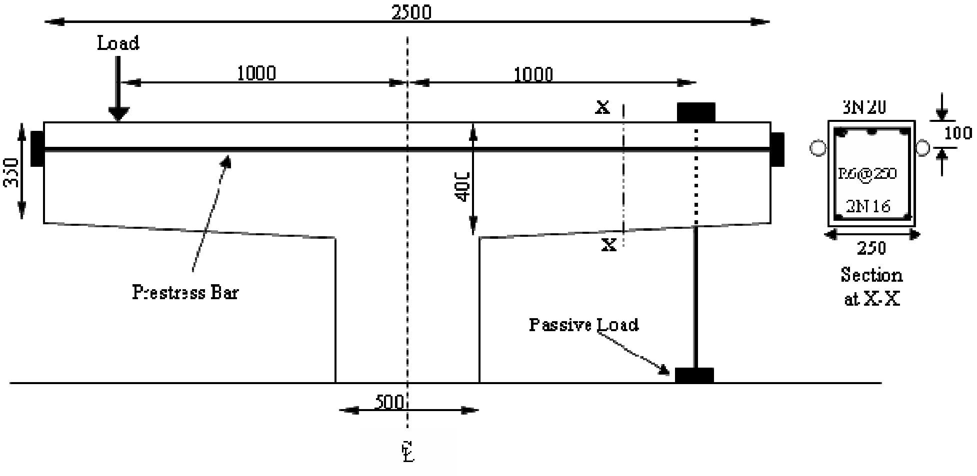

Fig. 1 Typical layout of preliminary experimental specimen

One specimen (PRCS1) served as control beam and tested without any strengthening or repair to obtain the exiting member capacity. The main parameter considered in the preliminary experiment was the external prestressing force. Different amount of external prestressing was applied to the specimens PRCS2 and PRCS3. The details are summarised in Table 1 below.

Table 1 Preliminary Experimental Variables

Specimen	Initial Loading	Prestressing Force (*kN*)	Remarks
PRCS1	-	-	Control Beam
PRCS2	Yes	150	Strengthened by External Post-tensioning
PRCS3	Yes	300	

Due to the limitation of loading facilities, the specimens were loaded using ‘active’ and ‘passive’ loads. One end of the cantilever was tied to provide a ‘passive load’, while the other end of cantilever overhang was loaded with an ‘active load’ using actuator. Both loads were applied at a distance of 1000 *mm* from the centre of the column support as shown in Fig.1. All specimens were loaded at a rate of 1 *mm/min*. The loading of control beam, PRCS1, was continued to failure. The loading of other two specimens, PRCS2 and PRCS3, was stoped at about 80-90% of the failure load of the PRCS1 and the specimens were unloaded. This preloading was applied to simulate the existing shear crack in the member. Then, the two specimens were externally prestressed by 150 *kN* and 300 *kN* forces respectively. The two specimens, PRCS2 and PRCS3, were then reloaded until failure.

Results of Preliminary Experiment

In the control specimen, PRCS1, initially small flexural cracks appeared near to support pier. However, these cracks did not open further during the test. The first shear crack was developed at about 100 *kN* load, near the point of loading and moved down at an angle approximately 45^0 towards the headstock-pier joint as shown in Fig.2. It was fully developed at 120 *kN*. Maximum crack width of 2 *mm* was observed at the ultimate load of about 150 *kN* and decreased to 1 *mm* when the specimen was unloaded. Similar behaviour was observed for other two specimens during initial loading.

Fig. 2 Shear cracks in control specimen

Fig. 3 Shear cracks in after the repair of shear cracks by epoxy injection

After the application of 150 *kN* external prestress forces to the specimen PRCS2, the crack width was closed up to 0.5 *mm*. The same crack was reopened during the second stage of loading. The specimen was failed at a load of 180 *kN*.

An interesting response was observed for the specimen PRCS3. The specimen PRCS3 was initially loaded until 135 *kN*. However, after strengthened by 300 *kN* external prestress it could take only 105 *kN*, lower than its initial loading, before failure. That means, a significant reduction (-15%) in the member capacity caused by the strengthening. Therefore, the load and prestress were released and shear crack was repaired by epoxy injection. The repaired specimen was again strengthened by 300 *kN* post-tensioning and reloaded until failure. Now the specimen failed along a new crack (Fig.3) with less ductility and could take an ultimate load of about 200 *kN*. Further details on the experimental methodology and test results can be obtained from (Snelling, 2003).

The load-deflection behaviour of the three specimens was shown in Fig. 4. The effect of the shear crack could be clearly observed in the figure. Furthermore, the epoxy injection did not change the stiffness of the specimen, but it significantly increased the capacity. That shows the epoxy injection could eliminate the effect of shear cracks and bring as a new beam.

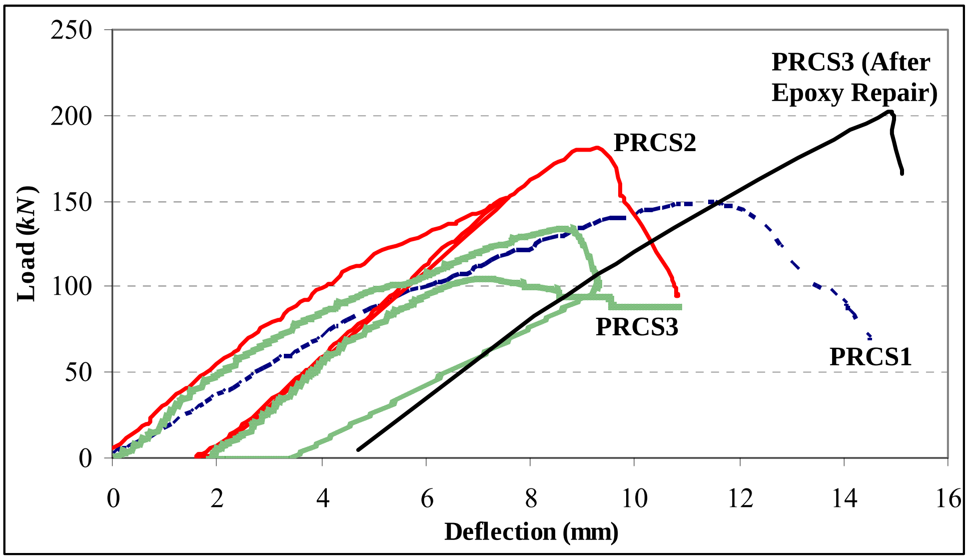

Fig. 4 Load-deflection response of shear specimens

MODEL TEST OF TENTHILL CREEK BRIDGE HEADSTOCK

A few bridges in Australia have been strengthened using the conventional external post-tensioning technology. One such example is the strengthening of the headstocks of Tenthill Creek Bridge. This bridge is located approximately three kilometres west of Gatton in Southeast Queensland. These piers consist of a cap beam, or headstock, supported by two rectangular shaped piers. Heavy loading on this bridge has caused substantial shear cracking in the headstocks.

To verify the applicability of the external post-tensioning strengthening system, tests were conducted on ¼ scale model of the Tenthill Creek Bridge headstock. Three model specimens were tested with the test variables being repairing of crack and strengthening by prestressing. All three specimens were constructed with a uniform rectangular cross section of 420x220 *mm*. Each specimen was 2300 *mm* long. Fig. 5 shows the typical layout of the specimen and reinforcement details. Though Y type bars have been used in the actual bridge, due to non-availability of such bars at the time of the experiment, N type (f_{sy} = 500 *MPa*) bars were used. The area of steel was approximately scaled down to 1/16 of the actual bridge to reflect the dimensional scaling.

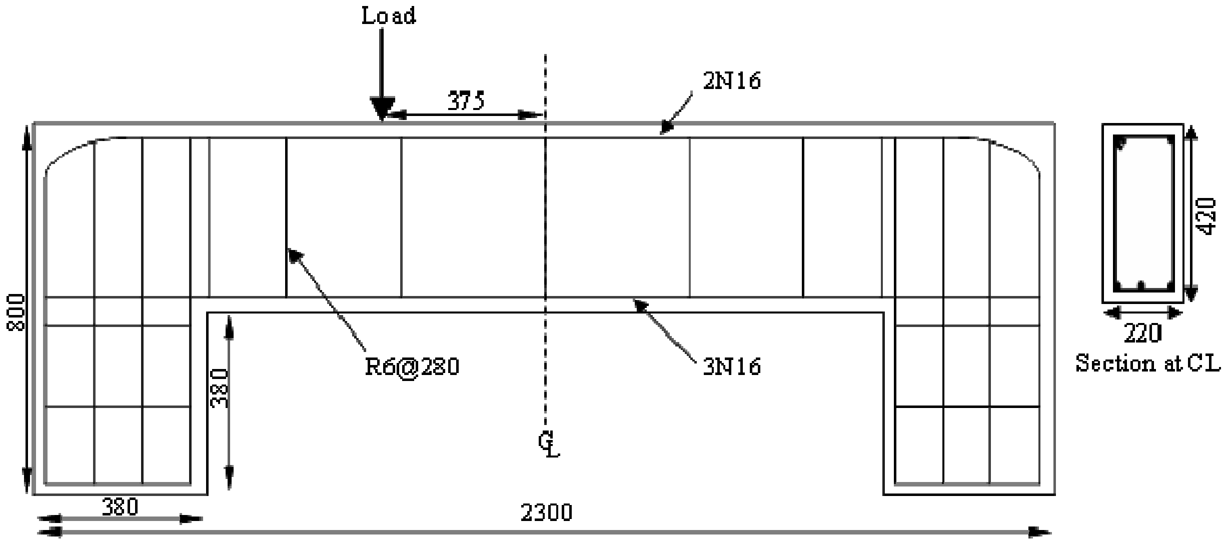

Fig. 5 Typical layout of scaled model of Tenthill Creek Bridge headstock

Test variables of the specimens are summarised in Table 2. Loading was applied non-symmetrically as shown in Fig. 5 and 6, at a distance 2/3 of span. This was based on the position of the main girder on the actual bridge that caused cracking in the headstock. The first specimen (control specimen) was loaded up to failure, without any strengthening. The other specimens were initially pre-loaded to cracking and later strengthened with external post tensioning. In the third specimen in addition to prestressing, cracks formed during the pre-loading were repaired by epoxy injection as shown in Fig. 7.

Table 2 Experimental Variables for Model Test

Specimen	Initial Loading	Strengthening	Epoxy Repair
THM1	x	x	x
THM2	√	√	x √
THM3	√	√	√

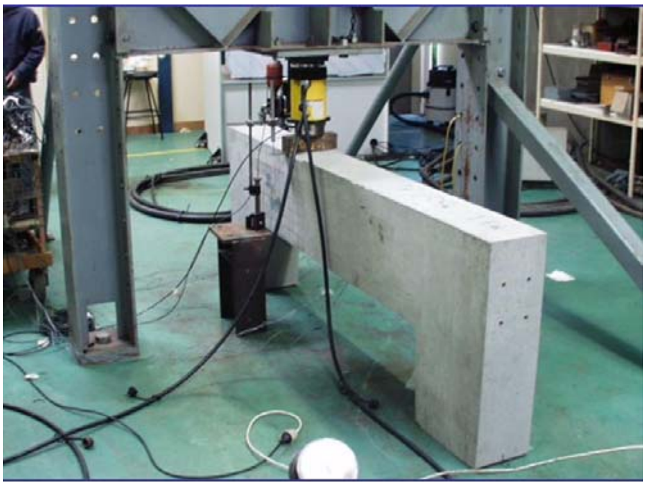

Fig. 6 Loading arrangement for the model test

Fig. 7 Repair of shear crack by epoxy injection

<u>Results of Model Test</u>

The unsymmetrical loading caused an interesting observation in the crack pattern of the control specimen, THM1. When the load was about 80 *kN*, small flexural cracks were observed at bottom of the specimen. However, these cracks did not propagate after the initial shear crack appeared. As the load was increased, a shear crack appeared in the short shear span at a load of 125 *kN*. It was noted that the crack formed on the shorter shear span was very similar that was found in the actual bridge. However, as the load was increased further (approximately 230 *kN*), a new shear crack developed in the long shear span and continued to fail. When the load reached 366 *kN*, the member failed along this crack plane. The remaining shear crack was approximately 4 *mm* wide at failure. This failure mode known as diagonal tensile failure of concrete member in the longer shear span (Kong & Evans, 1993).

The second specimen THM2 was initially loaded to develop a shear crack. The behaviour and cracking during this initial loading were found as similar as THM1. After the specimen was post-tensioned with 250 *kN*, the major shear crack in the long span closed to 0.2 *mm*. Then the specimen was reloaded and almost immediately the same cracks began to reopen (Fig. 8a) and lead to fail. It was also interesting to note that while loading the crack in the short shear span also reopened. Once loading had ceased, the width of this crack was in the vicinity of 0.9 *mm* wide. Most of this deformation occurred shortly after loading commenced.

Fig. 8a Failure of headstock along the longer shear span (without epoxy repair)

Fig. 8b Failure of headstock along the shorter shear span (with epoxy repair)

Specimen THM3 was also initially preloaded to produce the shear crack. The crack pattern that was produced during preloading was similar to that seen in specimens THM1 and THM2. Then specimen was unloaded and cracks were repaired by epoxy injection. At the same time, the failed specimen THM2 was also injected with epoxy resin. Once the resins were cured, the specimens were post-tensioned and loaded again. When loading was increased the initial crack in the short shear span appeared. However, as the load was increased, the crack continued to gradually open. The shear crack in the longer span did not develop during the test. Finally, the specimens failed through the crack at short shear span (Fig. 8b). It is evident that the epoxy injection was properly done and the injection process reformed the bond between the crack faces. The behaviour of both repaired specimens THM2 and THM3 was very similar even though the ultimate load of repaired THM2 was increased by 68%, while THM3 was increased by 46% as shown in Table 3.

Table 3 Summary of Results for Model Test

Specimen	f'_c (*MPa*)	Load (*kN*)		Load Increase (%)
		Initial	Ultimate	
THM1	22.2	-	366	
THM2	18.8	250	333	33
			420	68
THM3	27.0	423	546	46

The load-deflection response of the model test is shown in Fig. 9. Once again, the effect of existing shear crack and the epoxy injection could be seen clearly. The test results are summarised in Table 3. Further details about the model test can be obtained from (Aravinthan & Heldt, 2005; Woods, 2004).

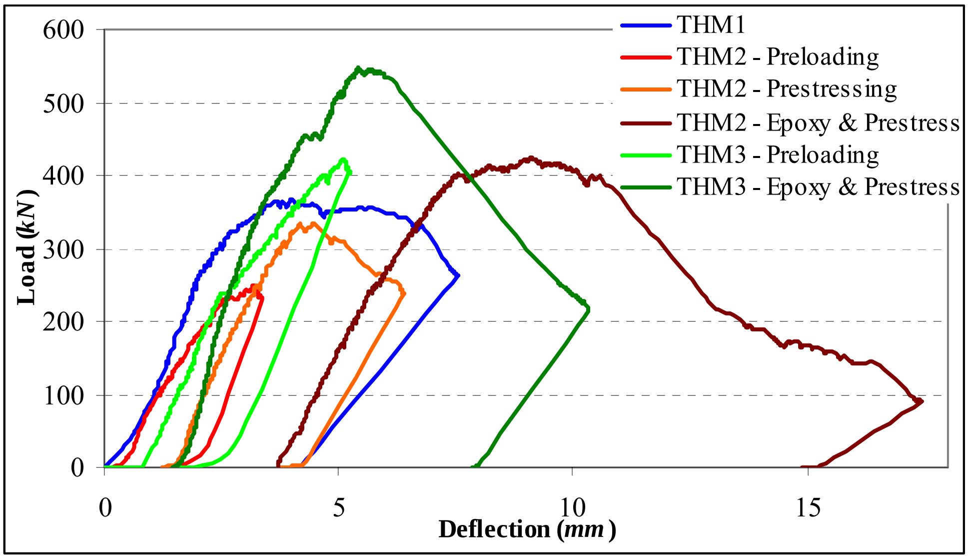

Fig. 9 Load–Deflection Response of Specimens

Compared with the preliminarily test series, it was further evident from the model tests that the failure mode could completely change when the specimens are properly repaired with epoxy injection. However, the effectiveness could not be fully evaluated due to the variation found in the concrete strength of the three specimens, as they were cast from different batches of concrete on different days. To overcome this issue, additional tests were conducted using smaller size specimens as explained in the following section.

FURTHER TESTS TO CONFIRM PREVIOUS FINDINGS

It was noted in the previous experiments the concrete strength could significantly affect the test results, especially when estimating the shear strength. Therefore, additional tests were carried out using model beams. These results were further investigated by testing a set of reinforced concrete beams with symmetric loading. For this purpose, four reinforced concrete beams with rectangular cross section of 300x150 *mm* were constructed. Each beam was 2500 *mm* long. For shear reinforcement, R6 bars were provided at 250 *mm* spacing in the shear span and at 100 *mm* near to the ends. Fig. 10a 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* (Fig. 10b). In this experiment all four beams were prepared at the same time and were cured under the same conditions to make sure that the concrete strength was nearly the same. The test variables are summarised in Table 4. Totally, 150 *kN* force was applied through the external rods (about 75 *kN* in each).

Table 4 Test Variables for Additional Tests

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

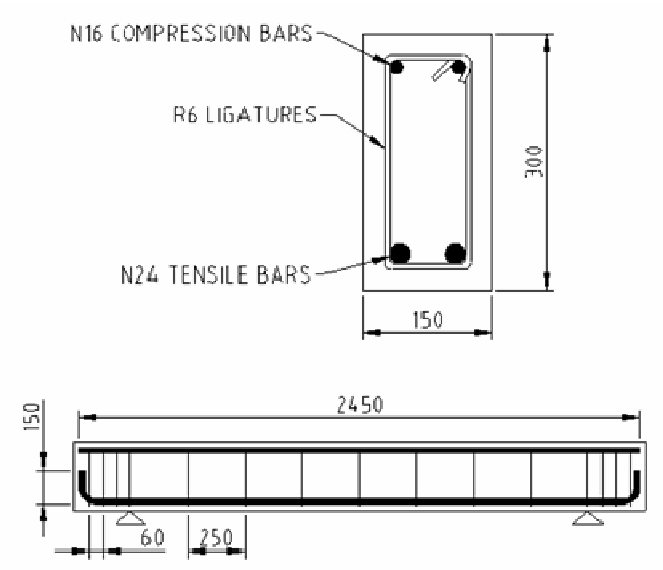

Fig. 10a Typical layout of the beam

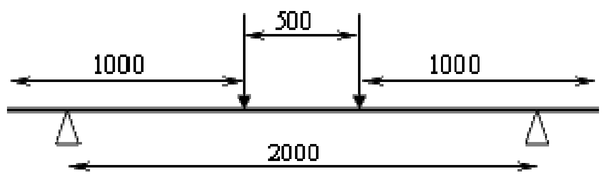

Fig 10b Typical loading arrangement

Results of Test of RC Beams

Very similar behaviour was observed as earliest experiments in the crack formation. The flexural cracks, which appeared in early stage of loading, did not develop further as the load was increased. The member capacity of the control beam was found as 196 *kN*. The maximum crack width at failure was 2.5 *mm*. The other two beams, RCB2 and RCB3, were initially loaded up to 90% of its capacity (about 180 *kN*) to simulate the initial cracks. The RCB2 failed at a load of 194 *kN*, slightly lower than the load on control beam. At the maximum load, the crack width was found as 3 *mm* and it further increased to 8 *mm* at failure. In the epoxy repaired specimen, RCB3, the repaired crack did not open-up again during the subsequent loading, which is very similar to the model test of the Tenthill Creek Bridge headstock. This proved that the epoxy repair was properly done. Furthermore, it has increased the capacity of the member to 310 *kN*, nearly 60% increment of control beam. At the maximum load, the crack width was found as 3 *mm* and it was 7 *mm* at failure. The last beam, RCB4, was tested to obtain the effect of external post-tensioning in the uncracked reinforced concrete beam. The beam could achieve ultimate load of 354 *kN* before it failed in shear. The failure mode of RCB4 was similar to the failure mode of RCB3, which can be noticed in Fig. 11. The ultimate loads of each specimen are tabulated in Table 5. It clearly shows that without repair the 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 strengthened by external post-tensioning. Further details about the on the experiment is reported by Luther (Luther, 2005).

Table 5 Summary of Results for Additional Tests

Specimen	f'_c (*MPa*)	Prestressing force (*kN*)	Ultimate load (*kN*)	Change (%)
RCB1	39.9	-	196	-
RCB2	40.3	152	194	-1
RCB3	40.4	150	310	58
RCB4	40.4	152	354	81

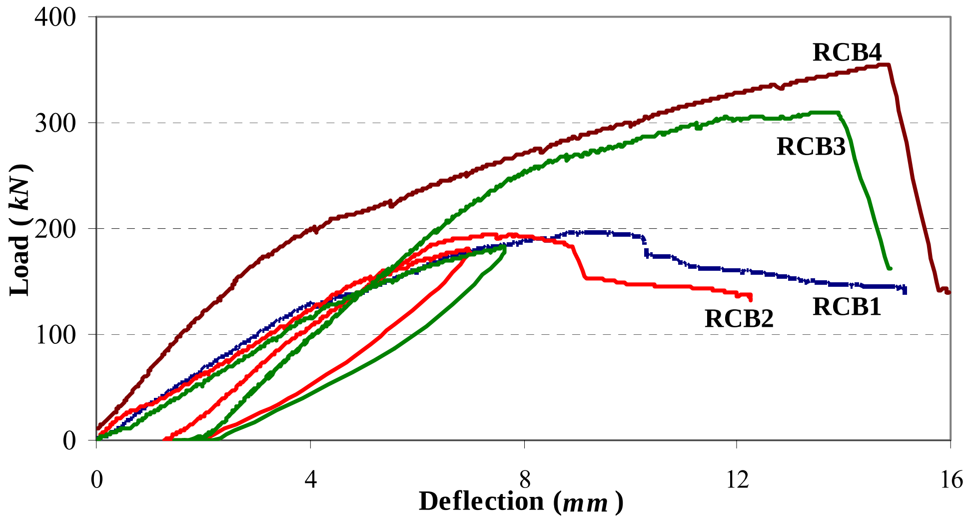

Fig. 11 Load–Deflection Response of RC Beam Specimens

This series of tests clearly demonstrates the effectiveness and importance of crack repairs when shear cracks are present. It also shows that by properly repairing the cracks, the beam could be restored and will behave similar to a new beam strengthened by external post-tensioning.

OVERALL DISCUSSION OF TEST RESULTS

All of the experiments show a very similar result on the effect of the existing shear cracks in a reinforced concrete member strengthened by external post-tensioning. The following features were observed from the experimental results.

- Existing shear cracks (without repair) have substantial effect on the member capacity of the reinforced concrete beam strengthened by external post-tensioning. It also observed that, even with higher prestressing force the member capacity could not increase. In some cases, the un-repaired shear crack may cause negative effect on the member capacity when strengthened with higher prestressing force.
- 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 method for repairing shear cracks.

It is clearly understood the shear strengthening of a reinforced concrete member by external post-tensioning is quite different from that of flexural strengthening. The previous studies on flexural strengthening were concluded that the flexural cracks could almost close by the application of external prestressing and have no effect in the capacity. 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. It causes significant reduction in the capacity of the member. In some cases it may also cause a negative effect in the shear capacity.

The Queensland Department of Main Roads has recently upgraded the headstocks of the Tenthill Creek Bridge with the conventional external post tensioning. Fig. 12 shows the Tenthill Creek bridge headstocks after strengthened by external post-tensioning. It can be seen that the existing cracks have been repaired by epoxy injection. In this particular bridge, the external post-tensioning was provided using high strength prestressing steel rods. These rods were protected from corrosion by providing an encasement that has been grouted.

Fig. 12 Strengthened headstocks of Tenthill Creek Bridge by external post-tensioning

CONCLUDING REMARKS

An extensive experimental study has been carried out to investigate the effectiveness external post-tensioning for shear strengthening of concrete structural elements. Based on three different types of specimens, following overall conclusions are drawn.

- External post-tensioning is a viable technology for shear strengthening.
- However, the effectiveness of this technology is greatly influenced by the presence of existing shear cracks.
- The existing shear cracks need to be appropriately repaired using techniques such as epoxy injection to fully utilise the external post-tensioning technology for strengthening.
- When the cracks are properly repaired and strengthened with external post-tensioning, the failure mode of the structure could be changed under some loading conditions.
- Further numerical investigation is recommended to study the effect the inclination and width of existing shear cracks.

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