

EFFECTS OF EXISTING SHEAR DAMAGE ON EXTERNALLY POST TENSIONED REPAIR OF BENT CAPS

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ABSTRACT

External post-tensioning can be considered an effective strengthening method for bridge members, which are deteriorating due to extreme loading conditions and progressive structural aging. The effects of existing shear cracks in bent caps strengthened by external post-tensioning were experimentally investigated using model specimens. Initial investigation revealed that the shear capacity of a bent cap is not enhanced by external post-tensioning only, when shear cracks exist. Moreover, it was found that the repair of existing cracks using epoxy injection substantially increases the shear capacity of the bent cap. The Tenthill Creek Bridge in South East Queensland, Australia provides a case study where the bent caps have been strengthened by external post-tensioning. The model tests of the bridge bent caps confirmed the initial findings on the effects of existing shear cracks on the shear capacity. The experimental results emphasize the need for appropriate repair of existing shear cracks prior to strengthening by external post-tensioning to enhance the shear capacity of bent caps.

CE Database Subject Headings: external prestressing, shear strength, bridges, strengthening, cracks, repairs, epoxy injection

INTRODUCTION

Over the last few decades, there has been a rapid increase in the volume and weight of heavy vehicles using road networks. Coupled with this is the fact that more than 50% of the bridges worldwide are over forty years old. The deterioration of these existing bridges due to increased traffic loading, progressive structural aging, and reinforcement corrosion from severe environmental conditions has become a major problem in most countries. Furthermore, the number of heavy trucks and the traffic volume on these bridges have resulted in extreme

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loading conditions that exceed their original design parameters. In some cases, such extreme loading had resulted in cracks that require urgent repair and rehabilitation.

External post-tensioning is considered to be one of the most appropriate techniques for strengthening or rehabilitating existing structures. Over many years, extensive research has been conducted on the flexural behavior of reinforced concrete members strengthened by external post-tensioning (Aravinthan et al. 2005; Harajli 1993; Mutsuyoshi et al. 1998). However, there has been relatively limited research on the shear strengthening of concrete members using external post-tensioning. While some studies claim that the shear capacity of reinforced concrete beams could be improved by external post-tensioning, the effects of existing cracks have not been evaluated in most of the previous studies (Tan and Ng 1998; Tan and Tjandra 2002).

This study aims to investigate the effects of existing shear cracks in the bridge bent caps, which are usually subjected to substantial shear forces, when strengthened by external post-tensioning. The experimental study was conducted in two parts; first, an initial investigation of a typical bent cap and then a model test of an actual bridge bent cap that was strengthened by external post-tensioning. The initial phase was conducted to gain insight into the effects of existing shear cracks and the amount of initial prestress on the increase in strength of the bent caps. Based on the findings from the initial phase, the Tenthill Creek Bridge was used as a case study where this bent cap was to be strengthened by external post-tensioning. Scaled model tests of the bridge bent cap were conducted to further investigate the effect of existing cracks and its repair on the failure mode of the structure. The results of these experimental investigations into the influences of existing shear cracks when strengthening a structure with external post-tensioning are presented in this paper. The importance of repairing shear cracks before strengthening by external post-tensioning is discussed and shown to significantly influence the behavior and failure mode of the structure.

REVIEW OF PREVIOUS INVESTIGATIONS

External post-tensioning is an established technique for flexural strengthening of girders (Harajli 1993). However, only a limited number of studies have been conducted on shear strengthening of reinforced concrete members by external post-tensioning. These investigations confirm that only a few have attempted to simulate the effects of existing cracks on the behavior of concrete members.

Harajli (Harajli 1993) performed experimental and analytical studies on flexural strengthening of reinforced concrete beams with existing flexural cracks strengthened by external post-tensioning. He tested 16 beams in total with two different external prestressing profiles: a straight horizontal tendon profile and a single-point

draped tendon profile with a saddle (deviator) at mid span. Each specimen had a 127x229 *mm* rectangle cross section and was simply supported over a 3000 *mm* span. To simulate actual conditions of flexural members, large fatigue deformations were induced prior to the external post tensioning by subjecting them to between 5000 to 10000 cycles of large amplitude fatigue loading at constant load range, which varied from 30% to 80% of the calculated ultimate flexural load capacity of the specimens. All specimens were loaded in four-point bending using two symmetrical concentrated loads applied at one-third the span length. He reported that, the external post tensioning had increased the flexural resistance of the specimens by up to 146%. He also observed that the width of the existing cracks was reduced or completely closed by the external post-tensioning; therefore, the existing flexural cracks had no significant effect on the capacity of the reinforced concrete beams strengthened by external post-tensioning. These experimental results were also verified by Pisani (Pisani 1999) using numerical analysis. However, it should be noted that the focus of these investigations were on the effects of existing flexural cracks when strengthened by external post-tensioning.

Teng et al (Teng et al. 1996) reported an experimental study on the performance of strengthened pre-cracked concrete deep beams under shear. They introduced vertical clamping to reduce the effects of the shear cracks in prestressing concrete, and tested 18 prestressed and non-prestressed concrete deep beams to failure followed by strengthening and retesting to failure for a second time. From the experimental results, they concluded that vertical clamping significantly increased the shear capacity and eliminated the effect of the existing shear cracks in the concrete member. A similar study has been independently performed by Khaloo (Khaloo 2000), in which he tested 24 reinforced concrete beams with dimensions 80x150x1800 *mm* under different test variables. These included concrete compressive strength, shear span to effective depth ratio (a/d), longitudinal tensile reinforcement, level of post-tensioning (as percentage of concrete strength), amount of shear reinforcement and use of external clamping. Khaloo reported that in the presence of post-compression stress, as low as $0.04f_c$ for strengthening, shear strength increases significantly and the mode of failure of the beams changes from brittle shear to ductile bending. These two studies have used external post-tensioning or clamping in the vertical direction to provide additional shear strength.

With the exception of the two investigations mentioned above that involved vertical clamping or prestressing, no significant studies investigating the effects of existing shear cracks in reinforced concrete members strengthened by external post-tensioning have been reported. While the provision of vertical rods/clamps increases the shear capacity of a member, provision of external post-tensioning in the horizontal direction may not only could increase the shear capacity, but also the flexure capacity of the member. Hence, an attempt has

been made in this study to evaluate the effects of existing shear cracks in bent caps when they are strengthened with external post-tensioning.

INITIAL INVESTIGATION ON STRENGTHENING OF BENT CAPS

Bridge bent caps need to be strengthened in flexure as well as in shear, due to the nature of the structural element. An experimental investigation was conducted to study the effectiveness of external post-tensioning for flexural strengthening of bent caps in concrete bridges. It was observed that the existing flexural cracks do not influence the strength increase because the flexural cracks tend to close themselves when external post-tensioning is applied in the horizontal direction (Aravinthan et al. 2004). However, the presence of shear cracks, which are usually inclined, could substantially influence the behavior of the structure when post-tensioned in the horizontal direction. An initial investigation was conducted to study this effect, which is discussed in the following sections.

Experimental Setup for the Initial Investigation

The experimental program involved three reinforced concrete cantilever bent cap specimens with rectangular cross sections throughout the whole length of 2500 mm. All specimens were of tapered shape cantilevers with cross sections of 350x250 mm at the toe end and 400x250 mm at the heel end as shown in Fig. 1. Sufficient longitudinal reinforcement was provided to ensure that the specimens fail in shear. The test parameters are summarized in the Table 1. With available loading facilities, the specimens were loaded on one end of the cantilever, while the other end was anchored to a strong floor, thus providing a 'passive load'. The distance between the loading point and anchoring point was 2000 mm. Fig. 2 shows the typical experimental setup and loading arrangement. The specimens were loaded by displacement control method using the actuator. The loading was applied until shear cracks developed in the bent cap. After cracking, the loading of control specimen RCS1 was continued to failure, while specimens RCS2 and RCS3 were unloaded. These two specimens were then externally prestressed by 150 kN and 300 kN, respectively. These specimens were reloaded further until the shear crack expanded substantially to the point where the specimens could not take any more load. Two load cells were attached to the end of each prestressing rod to measure the changes in the prestress force.

Initial Test Results and Discussion

In the control specimen, RCS1, initially small flexural cracks appeared on the tension zone near the column face. However, these cracks did not open further during the test. At about 100 *kN* load, a shear crack started to develop at the point of loading and moved down at an angle approximately 45° towards the bent cap-pier joint (Fig.3). It was fully developed at 120 *kN* load. Maximum crack width observed was 2 *mm* at the ultimate load of 149 *kN* but decreased to 1 *mm* when the specimen was unloaded. Similar behavior was observed for other two specimens in the preloading stage. After the application of 150 *kN* external prestressing to the specimen RCS2, the crack width was reduced to 0.5 *mm*. The same crack was re-opened during the reloading of this specimen. The specimen accepted a load of 180 *kN* before failure. The strength increase is about 20% higher compared with that of the un-strengthened beam.

The behavior of the third specimen RCS3 was expected to be similar, with much higher strength increase due to the increase in initial prestress to 296 *kN*, which is almost double the amount of that used in RCS2. However, the response observed for the specimen RCS3 was very different to that of RCS2. The specimen RCS3 was initially loaded until 135 *kN*, where an approximately 2 *mm* wide shear crack was created. Even though it was strengthened with 296 *kN* external post-tensioning, the crack width closed up to approximately 1 *mm*, still quite a large crack for the amount of prestress applied. The maximum load that could be applied after post-tensioning was only 105 *kN* load, which is lower than the maximum load achieved during the pre-loading stage. The same crack expanded and opened up to approximately 2.5 *mm* width during the re-loading stage. This means that, a significant reduction (-15%) in the member capacity resulted even after strengthening by external post-tensioning. What was also observed was the considerable deflection at the loading point of the cracked section due to the applied load. Noting that the width of the shear crack was still large (1 *mm*) after prestressing, the additional prestress force was in fact counterproductive, creating larger cracks when loaded again.

This experiment demonstrates the phenomena of the contribution of aggregate interlocking in the shear capacity of a RC member strengthened by external post tensioning. The aggregate interlocking depends on many parameters including aggregate size, concrete strength, crack inclination and crack width. As the crack width increases, the aggregate interlocking will decrease, which will lead to a drop in the maximum force that could be transferred across the crack. In the specimens RCS3, the inclination of the crack was flatter and the crack width was larger than RCS2. Therefore, the capacity could not be increased even with higher prestressing force. The application of higher axial force across a flatter, larger inclined crack also caused a negative effect in the shear capacity due to possible slip in the crack plan as discussed by Collins et al (Collins and Mitchell 1991). Hence,

it is important to prevent the slip along the inclined cracks by a suitable repair method, for externally post-tensioned strengthening to be effective.

In a further attempt to strengthen this specimen, an epoxy treatment was used to repair the shear cracks as shown in Fig. 4. Initially, the cracks were sealed by a two part structural epoxy adhesive (Lokset E). After two days, a low viscosity epoxy (Nitofill LV) was injected through injecting points provided along the cracks (see Fig. 4). The low viscosity epoxy is capable of repairing cracks as small as 0.2 *mm* wide at the surface tapering internally down to 0.01 *mm* wide. The epoxy resin was injected from the lower part of the crack to ensure the crack was properly filled with the resin. The epoxy repair method has been detailed elsewhere (Wood 2004). After curing of the epoxy, 295 *kN* prestressing force was reapplied and the specimen was re-tested to failure. A new shear crack with a slightly flatter angle developed in the specimen above the repaired crack as shown in Fig. 5. This is an effect of the change in principle stress direction due to the axial force induced by the external post-tensioning. The maximum load during the re-testing was 201 *kN*, which is 49% higher than the maximum load applied during the pre-loading stage.

The load-displacement behavior of all the three specimens is depicted in Fig. 6 and results summarized in Table 1. From Fig 6, it can be noted that the epoxy injection does not change the stiffness of the specimen, but it significantly increases the capacity. It is also important to note the change in the prestress force after strengthening as shown in Fig. 7. In specimen RCS2, this force increased from 150 *kN* to 195 *kN*, which is 30% higher than the initial prestress. For specimen RCS3 without repairing of cracks, the increase was only marginal, varying from 296 *kN* to 307 *kN*. However, the increase was substantial from 295 *kN* to 362 *kN* after repairing the cracks in specimen RCS3, which is denoted as RCS3* in Table 1, Fig. 6 and Fig. 7. It could be noted that when the cracks were not repaired, there is no apparent increase in the prestress force up to a deflection of about 2 *mm*. Only at larger deflections, specimens RCS2 and RCS3 showed some increase in the prestress force. This non-increase in RCS2 and RCS3 can be attributed to the possible slip along the inclined shear cracks. At larger deflections, the prestress force is increasing due to increase in chord distance of the prestressing bars. However, in specimen RCS3* there is gradual increase in the prestress force, which indicates that the epoxy injection has been effective in preventing the possible slippage at the cracked plane.

From the initial experimental investigations, it was found that the existing shear cracks significantly influences the capacity of the concrete members strengthened by external post-tensioning. Moreover, it demonstrates that the proper repair of existing shear cracks using epoxy injection could substantially increase the capacity of the

member strengthened by external post-tensioning. These findings were utilized in a subsequent investigation, where bent cap strengthening of the Tenthill Creek Bridge was used as a case study.

CASE STUDY OF STRENGTHENING OF BENT CAP OF TENTHILL CREEK BRIDGE

A few bridges in Australia have been strengthened by external post-tensioning technology and one such example is the strengthening of the bent caps of Tenthill Creek Bridge (Fig. 8a). Heavy loading on this bridge had caused some substantial shear cracking in the bent caps as shown in Fig. 8b. The crack extends from the edge of the pier to the location of the main girder on top of the bent cap and was approximately 1600 mm long and 0.5 mm wide. After analyzing the condition of the bent caps, the Queensland Department of Main Roads decided to strengthen the bent caps using external post-tensioning.

MODEL TEST OF TENTHILL CREEK BRIDGE BENT CAP

Experimental Setup for the Model Test

To verify the applicability of the proposed strengthening system, tests were conducted on 1/4 scale model of the Tenthill Creek Bridge bent cap. The experimental program consisted of three specimens with rectangular cross sections of 420x150 mm throughout the whole length of 2300 mm. Though Y type bars (yield strength $f_{sy} = 400$ MPa) have been used in the actual bridge, due to non-availability of such bars at the time of this investigation, N type bars (yield strength $f_{sy} = 500$ MPa) were used. The area of steel was approximately scaled down to 1/16 of the actual bridge to reflect the dimensional scaling. N16 bars were used as main reinforcements while shear reinforcements were provided by R6 bars (mild steel; yield strength, $f_{sy} = 250$ MPa). The reinforcement details of the specimens are shown in Fig. 9.

Loading was applied asymmetrically at a distance of 375 mm from the center of the specimen as shown in Fig. 9. This was based on the position of the main girder in the actual bridge that caused cracks in the bent caps. The first specimen (control specimen, RCH1) was tested under static loading up to failure, without any strengthening. The other two specimens (RCH2 and RCH3) were initially pre-loaded to cracking and later strengthened using external post-tensioning. Before prestressing, cracks formed during the pre-loading stage were repaired in the third specimen (RCH3) by injecting epoxy resin similar to specimen RCS3 in the initial investigation. The test parameters are summarized in the Table 2. The shear cracks in specimen RCH2 was further repaired after failure, by epoxy injection and retested, whose results are reported as RCH2*. As the specimens were constructed

individually using different batches of ready-mix concrete, there was a big variation in concrete strengths for the three specimens as shown in Table 2.

Model Test Results and Discussion

An interesting crack pattern was observed in the control specimen, RCH1 when loaded. Small flexural cracks appeared early in the loading stage, at about 80 *kN* load. However, these cracks did not propagate further when shear cracks began to develop. At a load of about 125 *kN*, a shear crack developed in the shorter shear span which was very similar to the shape of the crack found in the actual bridge. However, as the load was increased further to about 230 *kN*, a completely new shear crack developed in the longer shear span. The specimen failed when the load reached 366 *kN*, with the shear crack on longer shear span widening further to about 4 *mm*, as shown in Fig. 10, in a diagonal tension failure mode.

The second specimen RCH2 was preloaded up to 250 *kN* to initiate shear cracks, where the crack development was very similar to that of specimen RCH1. Then the specimen was unloaded and external post-tensioning was introduced. After the specimen was post-tensioned with a 239 *kN* force, the major shear crack in the longer shear span closed up to around 0.2 *mm*. It was observed that the major shear crack began to reopen almost immediately after reloading. The failure of the specimen was very similar to that of specimen RCH1, but at a lower load of 333 *kN*. The lower ultimate load can be attributed to the combination of possible slip at the inclined crack plane and the lower concrete strength of the specimen. In this specimen, the crack in the shorter shear span also reopened during reloading. Once unloaded, this crack closed up to about 0.9*mm* wide.

Specimen RCH3 was also preloaded as RCH2 to produce the shear cracks, which were very similar to the other two specimens. The specimen RCH3 was unloaded and cracks were repaired by epoxy injection. During this time, the failed specimen RCH2 was also injected with epoxy resin. Post-tensioning was introduced after curing of epoxy resins and the specimens were reloaded. As expected, an initial crack appeared in the short shear span when reloaded. Unlike RCH2, as the loading was increased further, the crack on the shorter shear span continued to become wider. The shear cracks that were repaired in the longer shear span region, did not reopen in the subsequent loading. Finally, the specimens failed in a shear compression mode with very large inclined crack in the shorter shear span that was different to the original crack during preloading as shown in Fig. 11. Crushing of concrete was also observed near the loading point. Both specimens showed very similar behavior after repairing with epoxy resin, even though the ultimate loads were different for the two specimens. The test results are summarized in Table 2.

Many test results have established that the failure mode is highly dependent on the shear-span/depth ratio (a_v/d) (Kong and Evans 1993, Collins and Mitchell 1991). In the model bent cap specimens, the a_v/d ratio of the shorter shear span was 1.2 while the ratio of longer shear span was 2.9, resulting in a diagonal tension failure along the longer shear span in the control specimen RCH1. Similar failure mode was observed in the specimen RCH2 although it was strengthened by external post-tensioning without repairing the cracks. This demonstrates that the external post-tensioning did not have any effect in the failure mode when the cracks were not repaired, as the same cracks began to open up further. However, when the cracks were properly repaired and post-tensioned, the failure mode changed to shear-compression failure in both specimens RCH2* and RCH3 with large cracks in the shorter shear span region and crushing of concrete in the compression zone. Such failure modes can be expected in a prestressed concrete member, which does not have any initial shear cracks. This clearly demonstrates that under asymmetric loading, the existing shear cracks can have significant influence in the shear failure mode when strengthened by external post-tensioning.

The load-displacement characteristics of the specimens are given in Figs. 12 to 14. The behavior of RCH1 is nearly linear during the initial stage of loading (Fig. 12). The development of crack could be identified from the graph by small dips from about 150 kN load. Between 250 kN and 300 kN, a number of these dips are evident and the slope of the plot begins to decrease. This corresponds to the stage at which major cracks began to appear in the longer shear span section. The load-deflection response of the second specimen, RCH2, is shown in Fig. 13. An increase in the capacity can be seen as each restoration technique has been applied to the specimen. After post-tensioning, the RCH2 accepted a maximum load of 333 kN, which is 33% higher than the preloading stage. Once the cracks were repaired by epoxy injection, the same specimen could take a load as high as 420 kN, which is 68% higher than the load at preloading stage. By comparing the three linear regions in the plots for specimen RCH2, slight changes in the stiffness of the member are evident. An increase in the member's stiffness can be seen after the application of post-tensioning as would be expected. However, the increase in stiffness after epoxy injection is only marginal in specimen RCH2*.

From the plot of third specimen, RCH3 (Fig. 14), it can be seen that the specimen had to be preloaded up to a load of 423 kN to obtain the same crack width as in RCH2. The higher loading is attributed to the much higher concrete strength in specimen RCH3 compared to that of RCH2. Once the specimen was injected with epoxy and post-tensioned, the maximum load was increased to 546 kN. This increase is only 29%, which is much less compared to specimen RCH2*. This could be attributed to the difference in strengths of concrete in these two specimens. A substantial decrease in load is evident subsequent to the specimen reaching its peak load. This is

explained by the breaking of one of the stirrups passing through the shear crack. It can also be seen that in specimen RCH3, a large increase in stiffness after the specimen was rehabilitated compared with RCH2*. This may be attributed to the crack width filled with epoxy. When this crack width is large, the increase in stiffness is relatively low (as in RCH2*) compared to the case of RCH3 where a smaller crack width is filled with epoxy.

The effect of the epoxy repair can also be seen in the changes in prestress force as shown in Fig. 15. Similar to the initial test results, the increase in prestress force in specimen RCH2 is only marginal, when cracks were not repaired. However, there was a significant increase in the prestress force in the specimen RCH2* and RCH3 when the cracks were repaired by epoxy injection. This non-increase in RCH2 can again be attributed to the possible slip along the crack plan, as explained in initial experimental results. Hence, it can be concluded that the repair of existing cracks is essential for strengthening by external post-tensioning to be effective and epoxy injection is a suitable technique to repair cracks in concrete specimens. This finding supports the test results reported by Pantelides et al, where epoxy injection of cracks were done for bent caps retrofitted with fiber reinforced polymer (FRP) composites over the cracked region for shear strengthening (Pantelides 2001). This also shows that retrofitting by FRP composites are possible as an alternative to external post-tensioning for strengthening of bent caps.

Practical Considerations

In the experimental procedure, the specimens were unloaded prior to epoxy repair or strengthening by post-tensioning, which may not be the case in a bridge bent caps, where substantial dead load will be imposed from the bridge superstructure. However, such effects are partly taken into consideration by overloading the specimens to create reasonably large cracks that do not close up completely when unloaded. It should be noted that while the addition of external prestressing increases the shear capacity, it could also lead to lower ductility of the member being strengthened. There was large variation in concrete strength in the specimens tested. By normalizing to a particular concrete strength, the effects could be further quantified. From the experimental results discussed above, it can be seen that the level of prestressing influences the performance of the bent caps with existing shear cracks. When the cracks are properly repaired, the level of prestressing for strengthening a bent cap will depend largely on various parameters including the existing concrete strength, equivalent stress in the critical sections and required increase in the capacity. There is a need to develop design and strengthening procedures when bent caps with existing shear cracks need to be strengthened by external post-tensioning.

CONCLUSIONS

This paper presented an experimental investigation of bridge bent caps strengthened by external post-tensioning using model tests. The effects of existing shear cracks on the behavior of such members and the importance of repairing such cracks were discussed. From the experimental results, following conclusions are drawn:

1. Existing shear cracks have substantial influence on the load carrying capacity of the concrete members strengthened by external post-tensioning. The width of existing cracks was also found to influence the behavior of such structures.
2. The proper repair of existing shear cracks can increase the capacity of a member as high as 70% when externally post-tensioned.
3. A suitable crack repair technique must be adopted for concrete members with existing shear damage, before attempting to strengthen by external post-tensioning. Epoxy injection technique was found to be effective for crack repairs in this study.
4. Under asymmetric loading conditions, the failure mode in shear could be significantly influenced by the presence of existing cracks when strengthened by external post-tensioning. The failure mode significantly changes when the existing cracks are repaired.

Based on the model test results, the bent caps of the Tenthill Creek Bridge were strengthened with the conventional external post tensioning, after repairing existing cracks by epoxy injection. It is believed that this investigation provides useful information to bridge engineers who are considering external post-tensioning and other strengthening methods to strengthen overloaded bridges.

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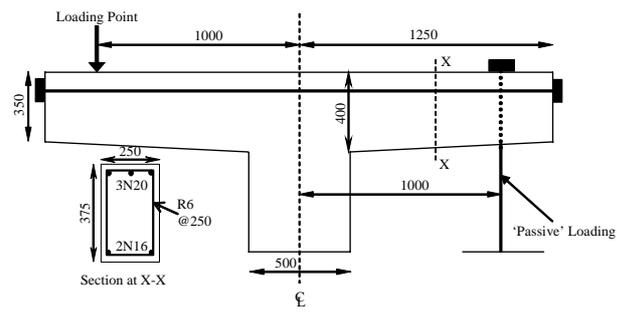


Fig. 1. Typical Layout of Initial Test Specimen



Fig. 2. Loading Arrangement for the Initial Test



Fig. 3. Shear Cracks in the Control Specimen RCS1



Fig. 4. Repair of the Shear Crack by Epoxy Injection



Fig. 5. New Shear Cracks in RCS3 after Crack Repair

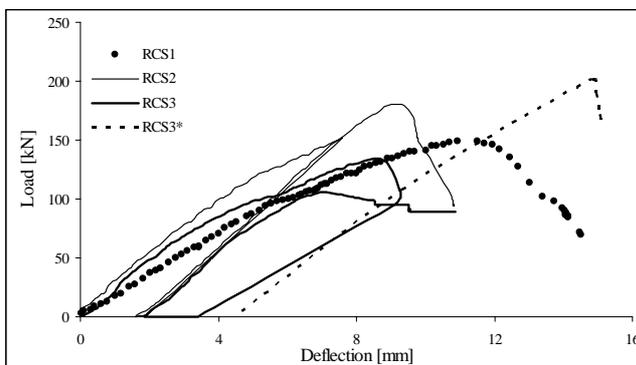


Fig. 6. Load-Deflection Response of Initial Tests

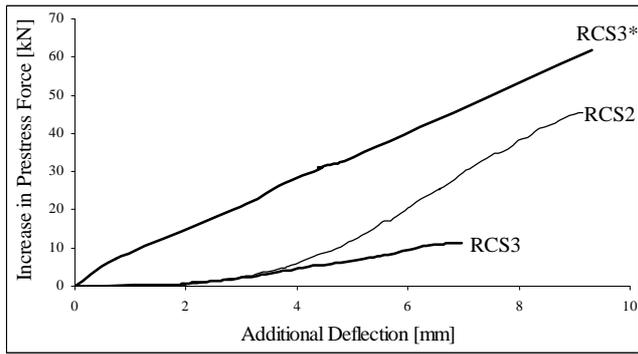


Fig. 7. Increase in Prestress Force in the Initial Tests

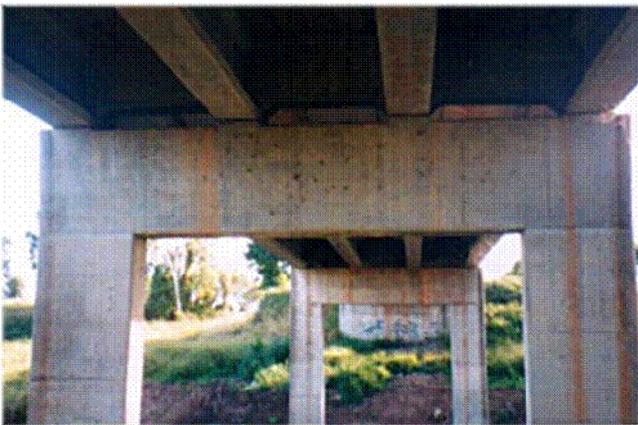


Fig. 8a. View of Tenthill Creek Bridge Bent Caps



Fig. 8b. Crack in Tenthill Creek Bridge Bent Cap (location highlighted)

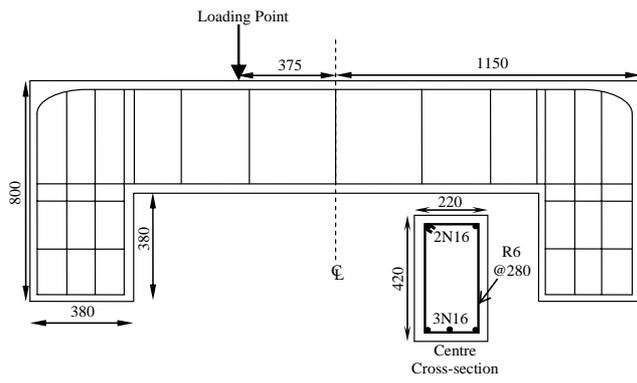


Fig. 9. Typical Layout of Model Test Specimen



Fig. 10. Failure of the Control Specimen RCH1



Fig. 11. Failure of RCH2* (after epoxy injection)

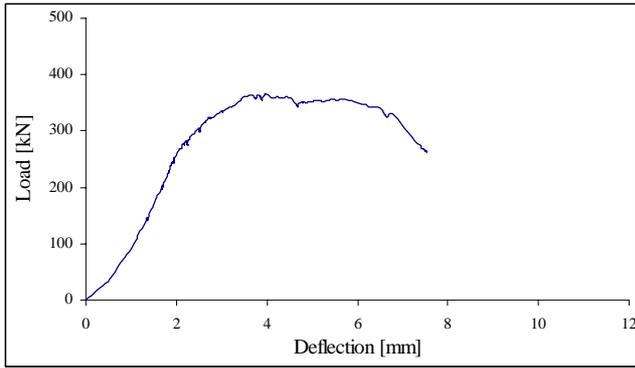


Fig. 12. Load – Deflection Response of Specimen RCH1

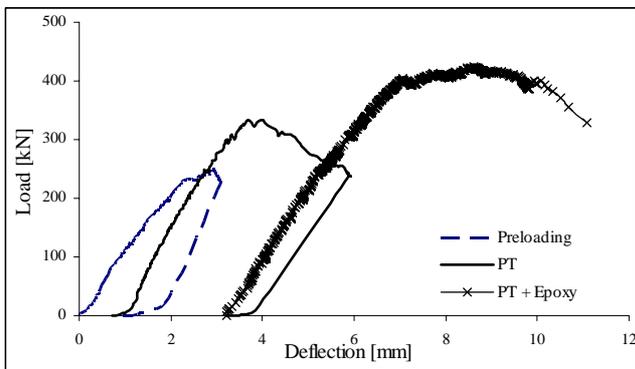


Fig. 13. Load – Deflection Response of Specimen RCH2

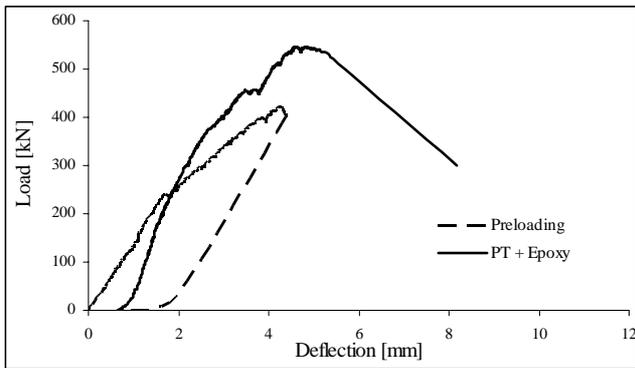


Fig. 14. Load – Deflection Response of Specimen RCH3

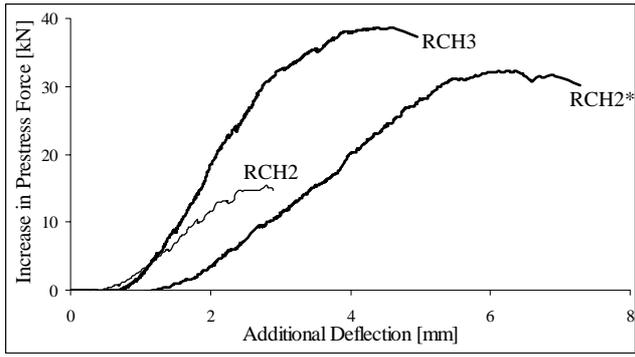


Fig.15. Variation of Prestress Force for Model Tests

Table 1. Summary of Initial Test Results

Specimen	f'_c (MPa)	Post-tension (kN)		Preload (kN)	Ultimate Load (kN)	Load Increase (%)	Deflection at loading point corresponds to Ultimate Load (mm)	
		Initial	Ultimate				Total	After Strengthening
RCS1	26.0	-	-	-	149	N/A	11.57	-
RCS2	33.0	150 (0.05 $f'_c A_g$)	195 (0.06 $f'_c A_g$)	150	180	20	9.15	7.55
RCS3	29.0	296 (0.10 $f'_c A_g$)	307 (0.11 $f'_c A_g$)	135	105	-15	7.11	5.25
RCS3*	29.0	295 (0.10 $f'_c A_g$)	362 (0.12 $f'_c A_g$)	135	201	49	14.86	10.18

Notes: * After epoxy injection

Table 2. Summary of Test Results of Model Bent Caps

Specimen	f'_c (MPa)	Post-tension (kN)		Preload (kN)	Ultimate Load (kN)	Load Increase (%)	Deflection at loading point corresponds to Ultimate Load (mm)	
		Initial	Ultimate				Total	After Strengthening
RCH1	22.2	-	-	-	366	N/A	3.99	-
RCH2	18.5	239 (0.14 $f'_c A_g$)	255 (0.15 $f'_c A_g$)	250	333	33	3.70	2.70
RCH2*	19.2	237 (0.13 $f'_c A_g$)	270 (0.15 $f'_c A_g$)	250	420	68	8.48	5.25
RCH3	29	245 (0.09 $f'_c A_g$)	283 (0.11 $f'_c A_g$)	423	546	29	4.63	3.89

Notes: * After epoxy injection