Long-Term Performance of a CFRP Strap Shear Retrofitting System

by N. Hoult and J. Lees

Synopsis: A shear retrofitting method for reinforced concrete (RC) beams has been developed that uses external CFRP straps to provide additional shear capacity. Research has been undertaken to develop an installation technique that allows the CFRP strap to encompass the full depth of the beam, without requiring access to the top surface of the beam. The current testing scheme investigates the durability of the CFRP strap system using the new installation technique. A long-term load test was conducted on a RC T-beam which indicated that the straps continued to provide shear capacity after 7 months under a load equivalent to 80% of the ultimate capacity of the retrofitted beam. A cyclic test conducted on another similar T-beam specimen demonstrated that after 1,000,000 cycles, under a load that varied between 0.5 and 0.8 times the ultimate retrofitted beam capacity, the straps continued to provide effective shear enhancement.

Keywords: beams; CFRP; concrete; fatigue; long-term; retrofitting; shear

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INTRODUCTION

It has been estimated that that cost of retrofitting reinforced concrete (RC) structures is $40 billion a year in the US alone (PCI 2003). While not all of this money is spent upgrading shear-deficient structures, even a small percentage still represents a considerable investment. Shear deficiencies are generally the result of increased load requirements or, as Collins and Mitchell (1997) note, the fact that previous design codes were less conservative than current codes. In some climates, corrosion of internal reinforcing steel due to the use of deicing salts is a further issue that can have a detrimental effect on shear capacity. Considering both the cost, and the number of structures involved, there is a need to find effective shear retrofitting systems for RC structures.

Current research efforts focus primarily on the use of Fibre Reinforced Polymers (FRPs) to enhance the shear capacity of RC beams. FRPs are not susceptible to corrosion and thus have an advantage over more traditional retrofitting techniques that use steel. FRPs are also lighter and will not contribute greatly to the dead weight of the structure. Triantafillou (1998), as well as many others, has looked at the use of FRP laminates or sheets that are bonded to the side of the specimen. The amount of shear force that can be transferred to the beam is dependent on the strength of the bond, the anchorage length, and the FRP strength and stiffness. If the anchorage length is insufficient, the FRP retrofit will delaminate before the ultimate capacity of the FRP is reached. However, anchorage length issues can be mitigated if the FRP laminates are wrapped around the full cross section. This also potentially provides better shear resistance according to Kani, Huggins, and Wittkopp (1979). They suggest that reinforced concrete beams can be considered as a series of arches, as shown in Figure 1, and that in order to prevent shear failure each of these arches must be tied together with transverse reinforcement. Thus failure of one or more of these internal arches is possible if the shear reinforcement does not encompass enough of the beam depth. In addition, with bonded systems there exists the potential for failure if the local strain in the FRP induced by crack formation exceeds the ultimate strain of the FRP or results in excessive debonding.

Another type of shear retrofitting technique uses Near Surface Mounted (NSM) FRPs. In this system, grooves are cut into the sides of concrete beams, FRP reinforcing bars are installed and then the grooves are filled with epoxy (De Lorenzis and Nanni 2001). Once again failure tends to be due to breakdown of the epoxy bond. De Lorenzis and Nanni also discovered that whilst strength enhancements of 41% were possible without penetrating the flange of their T-beam sections, increases of 106% were possible if the FRP bars were embedded into the flange. This further demonstrates the benefits of stirrups encompassing the full depth of the beam.

Previous research has highlighted the need to develop a system that is not susceptible to bond breakdown, loss of anchorage or localized strain concentrations due to crack formation. At the same time this system should achieve the beneficial effects that come from being able to encompass the complete web depth. A shear retrofitting system that meets this criteria was developed by Winistoerfer (1999) that involves wrapping thin CFRP thermoplastic tapes around a beam to form an external reinforcing element. The tapes are 12mm wide and 0.16mm thick. Because the tapes are so thin, they can be wrapped around a section with a minimum radius of 12.5mm up to 40 times with each layer providing a linear increase in tensile capacity. After 40 loops, the tensile capacity added by each additional layer is not as significant. The outermost layer of the tape is welded to the next outermost layer but the inner layers remain non-laminated. Winistoerfer discovered that although the outermost layer forms a closed loop, the inner layers act independently, each one reaching its maximum tensile strength. In contrast, if all the layers are fused together, through thickness effects reduce the capacity of each layer and the overall capacity of the strap. A further benefit is that the non-laminated straps can be prestressed. In the following, results from a series of experimental studies that have been carried out at the University of Cambridge using these straps as a shear retrofitting system for RC beams are presented. Of particular interest is the long-term durability of the CFRP strengthening system.

RESEARCH SIGNIFICANCE

Whilst previous experimental programs have shown that the prestressed CFRP strap retrofitting system enhances the shear capacity of shear-deficient concrete beams, the current work seeks to test the durability of these straps. This study takes initial steps towards establishing the long-term durability of CFRP strap systems and identifying key considerations that may need to be considered.

EXPERIMENTAL BACKGROUND

Kesse, Chan and Lees (2001) investigated the results of two RC T-beams tested in four point bending. The first served as a control beam and failed in shear at 100kN with a diagonal crack forming between the support and one of the load points. The second beam had three of the CFRP straps developed by Winistoerfer placed in each shear span. The straps were wrapped around the entire web and supported on profiled steel pads on the top and bottom of the beam as illustrated in Figure 2. The straps were prestressed with an initial force of 30kN (or approximately 60% of the ultimate strap capacity). The addition of these straps provided the beam with enough shear capacity to achieve a ductile flexural failure at a load of 150kN.

Kesse (2003) tested a series of rectangular RC cantilever sections. He looked at the effect of varying several strap parameters such as the strap spacing, strap stiffness and initial prestress. Once again, the straps were supported on metal pads on the top and bottom of the beam. Kesse concluded that in order to utilize the full capacity of the strap, they should be placed at a spacing no further than d apart, where d is the effective depth of the beam. He also concluded that stiffer straps, which are a direct function of the number of loops, were more likely to force a ductile flexural failure. Finally, he concluded that the level of initial prestress did not play a significant role in terms of the strengthened capacity of the beam. However, this result seems to be dependent on the beam geometry as work by Stenger (2003) showed that the shear capacity of deep beams wrapped with CFRP straps was influenced significantly by the initial amount of prestress.

Although the previous experimental studies have shown that CFRP straps have incredible potential as a retrofitting system, they have all been limited by the use of metal support pads. The use of these pads to support the straps, especially on the top surface of the beam, leads to serviceability issues for the structure. A freeway bridge with these pads, for example, would require an extra topping in order to ensure a smooth running surface for vehicles. The extra weight of the running surface could negate any improvement achieved by using this lightweight material. As well, any installation would require access to the top surface of the bridge, which could lead to significant traffic interruptions and additional costs.

In order to mitigate these problems, Hoult and Lees (2004) proposed a method of installing the CFRP straps that only required access to the under surface of a T-beam. The underslab retrofitting technique involved drilling holes into the flange of the beams. Although a number of hole configurations and installation methods were investigated, a system with grouted holes where the CFRP strap rested in a groove cast into the filling material showed the most promise. In practice, while the holes are being drilled and before the grout reaches full strength, temporary shoring should be provided if necessary. The study concluded that the depth of penetration into the compressive flange was important if full shear enhancement were to be achieved. Based on these experiments, the strap configuration shown in Figure 3 was developed after the paper by Hoult and Lees was published. Using this configuration, a ductile flexural failure was achieved with an ultimate specimen capacity of 135kN (an equivalent unstrengthened control beam failed at a load of 88kN).

While the static behaviour of the strengthening system was encouraging, the long-term performance is also important. Tests were therefore devised to investigate the behaviour of the strengthened beams under sustained load (long-term test) and also due to cyclic loading.

LONG-TERM TEST

Test Specimens

The beam cross section is illustrated in Figure 3. The material properties of the steel reinforcement are given in Table 1. The concrete strengths at the beginning of testing are given in Table 2 whilst Table 3 contains the CFRP strap properties. The strap layout is illustrated in Figure 4.

Strap Installation

In order to achieve the strap path illustrated in Figure 3, four holes in the concrete flange must be created. Although in the field all holes will have to be drilled, in order to protect the internal strain gauges, the two diagonal holes in the flange were pre-cast into the beam. This was achieved by wrapping round metal inserts in bicycle inner tubes and placing them in the formwork before casting. Two days after casting the metal tubes were removed and the bicycle inner tubes were pulled out, leaving behind two 30° holes in the flange. The vertical holes were drilled into the flange using a hammer drill with a 25mm diameter drill bit. The holes were drilled a minimum of two weeks after casting. Once the holes were drilled, a strip of 3mm thick and 15mm wide polytetrafluoroethylene (PTFE) was placed in the holes to create the void that the straps would later pass through. The holes were then filled with a high early strength, non-expansive concrete repair product. The product was vibrated into the holes to ensure maximum contact with the existing concrete and minimum voids. After one day the PTFE strips were removed leaving a void in the grout.

The CFRP straps were then threaded into this void and around the beam. On the underside of the web they were wrapped around a metal pad that prevented the strap from bending below its minimum critical radius of 12.5mm. Ten loops of CFRP tape were used for both the long-term and cyclic load test specimens. The CFRP thermoplastic tape was then welded together. As mentioned earlier, only the outer two layers need to be welded together to create a closed outer loop. Once the straps were welded, they were prestressed using the set-up shown in Figure 5. For convenience the experimental beam was turned over to install and prestress the straps, but this is not a necessity. The system uses an hydraulic jack to apply force through a threaded rod that lifts up the metal plate supporting the CFRP strap. The applied prestress was 15kN resulting in a strap stress of 390MPa (approximately 25% of the total strap capacity).

Test Set-Up

Two test specimens were considered. The first specimen was strengthened but unloaded and the strap strains were monitored with time. The second specimen was subjected to a shear force of 110kN. This force was chosen for several reasons. First of all, it was between the capacity of the unretrofitted specimen (Hoult and Lees 2004) of 88kN and the capacity of the retrofitted specimen, that failed in flexural, of 135kN. Work by Tilly (1979) suggests that the ratio of dead to live load applied to typical RC bridges is between 0.2 and 0.4. As a typical live load, the standard fatigue vehicle from BS 5400 (1980) was used. This vehicle has a weight of 80kN per axle, which when combined with a dead load calculated using Tilly's ratio results in two point loads of 110kN each (unfactored dead plus live load). It should be noted that the standard fatigue vehicle loading would not normally be applied to a beam of these dimensions. However, the loading provided for an extreme test of capacity as well as corresponding to the point at which significant strap strains were developed during the static tests.

The test set-up for the long-term test is illustrated in Figure 6. The beam was 3m long and had a clear span of 2.5m. The two point loads were applied 0.75m in from each support. In order to apply the 110kN of shear (and 220kN of total load) two special threaded rods were used. Each 30mm diameter rod was turned down in the middle and a full bridge strain gauge configuration was placed on the turned down area. The full bridge was then used as a load cell allowing the total force being applied to the beam to be measured. Each rod's 'load cell' was calibrated using a separate tensile testing machine. The rods were then screwed into the threaded sockets in the strong floor.

A cross beam and a spreader beam were used to transfer the load from the strong floor into the test specimen as illustrated in Figure 6. Once these beams were in place, the load was applied by tightening nuts on the threaded rods against the cross beam. In order to provide enough force, a wrench with a 2m long scaffold pole extension was used. The disadvantage of this system was that as the beam crept, the tension in the rods would reduce, which would in turn reduce the total force being applied to the beam. This meant that the nuts had to be periodically tightened to ensure that the 110kN of shear force was maintained in the test specimen. Although this situation is not ideal, the amount of shear force required made the use of dead weight for loading impractical.

The beam displacement was measured with a mechanical dial gauge. The strains on the internal longitudinal and transverse reinforcement were measured using 6mm strain gauges. The strains in the CFRP straps were also measured using 6mm strain gauges placed at the mid-height of outer layer on both sides of the beam. The applied loads as well as the strains were data logged at 6 hour intervals (see Figure 4 for the strain gauge locations).

Long-term behaviour

The strap strains plotted over time in the unloaded beam are given in Figure 7. In this case the strap strains have decreased with time by about 5% over 77 days. This reduction in strain is believed to be due to creep in the concrete under the prestressing force of the strap. At the same time, there may also be further losses due to relaxation in the CFRP strap. Whilst the strain gauge readings will not indicate relaxation, experimental work by Saadatmanesh and Tannous (1999) on CFRP prestressing rods indicate that relaxation losses can be between 5 and 10% of the prestressing force over a 50 year period. The strap strain with time results for the loaded beam can be seen in Figure 8. In this case, the CFRP strap strains have increased over time. The maximum strap strains have increased by approximately 0.001 or 23% after 220 days. As such, the true long-term strap strain increases would if anything be slightly larger than shown if the strain reductions due to concrete creep were removed. Interestingly, if the strap strains are plotted versus time on a logarithmic scale, the relationship appears to be linear as illustrated in Figure 9. Based on this relationship the maximum strap strains after 100 years would be 0.0076, which is less than the rupture strain of 0.01 suggesting that the strap may have the required long-term capacity. However, more work is still required to establish which parameters contribute to this relationship. If the strap strains were to eventually exceed the ultimate strain, the straps could fail, resulting in collapse of the structure. Thus, it is necessary to develop a method of calculating the long-term increase in strap strain so that the designer can have reasonable confidence in the durability of the straps.

The mid-span deflection vs. time relationship for the loaded beam is presented in Figure 10. After approximately 220 days, the loading has resulted in a total deflection of 24.1mm. Of greater interest is the increase in deflection of 8.7mm above the initial deflection of 15.4mm, representing an increase factor of 1.57.

A comparison of Figures 8 and 10 shows that the long-term deflection and strap strain relationships have the same general shape. The major difference is the magnitude of the increase, or factor, of the relationship. It is possible that a relationship could be developed to determine the long-term strap strains based on the deflection. However, a viable method of calculating deflections must first be determined before any such relationship could be considered. As such, the available methods for calculating deflections need to be examined.

Deflections due to flexure – According to most approaches, the deflection of reinforced concrete beams increases over time due to the creep and shrinkage of concrete (ACI Committee 435 2003). The creep in the concrete causes increasing strains in the longitudinal reinforcement, which translates to an overall increase in the beam deflection. There exist approaches (ACI Committee 435 2003) that are capable of estimating flexural deflections to a high degree of accuracy. Unfortunately they require a knowledge of the materials and environmental conditions that typically would not be available to a designer hoping to retrofit an existing 30-year-old structure. Instead it would seem more practical to use a simplified approach such as the ACI factor approach (ACI Committee 318 1995), given in equation 1, despite the lack of accuracy of such an approach (Espion and Halleux 1990). Safety factors could then be used to account for the inaccuracies in the method.

$$f_t = f_o\left(1+\frac{\xi}{1+50\rho_c}\right) \tag{1}$$

f_t = the deflection in mm at time t
f_o = the initial deflection in mm at time $t = 0$
ξ = a factor to account for the duration of loading
$\rho_c = A_c/bd$ = the compressive reinforcement ratio
A_c = the area of compressive reinforcement (mm^2)
b = the width of the web (mm)
d = the effective depth (mm)

The factor ξ is set to 2 for loads applied for more than 5 years.

Deflections due to shear -- Interestingly, the long-term deflection calculations in design codes are based on flexural effects. However, if the deflections of the long-term specimen investigated in this study were due exclusively to flexural effects, one would not anticipate any increase in strap strain because all the strain redistribution due to long-term effects would be primarily longitudinal. In fact, if anything, a slight decrease in strap strain due to creep in the concrete might be expected as illustrated in Figure 7. Thus the increase in strap strain suggests that there is a shear component to the deflection. This result has been verified by Nie and Cai (2000) who calculated deflections due to shear to be between 13 and 35% of the total long term deflection. However, Nie and Cai also suggest that the long-term change in transverse strain is negligible and that the increase in shear deflection is the product of creep in the concrete. As can be seen from Figure 8, this assumption is incorrect in this case, with the maximum strap strains having increased by approximately 23%. A similar increase in strain in the middle steel stirrup of 31% was also observed. An increase in transverse strains would seem logical if shear deformations are significant. Without an increase in the applied shear force, the only other way for the shear strains to increase (and thus the corresponding shear displacements) would be for the effective shear modulus of the concrete to decrease. An approach that is employed in Finite Element Analysis (FEA) is to reduce the shear modulus, G, by a factor, β, to account for cracking. A decrease in the shear modulus would suggest a reduction in the concrete's shear capacity and a corresponding increase in the transverse reinforcement stresses and strains under the same load.

Long-term strap strains – The preceding discussion has illustrated the need for a method of calculating long-term deflections that is both straightforward and accounts for the shear component of the deflection. Unfortunately there is currently not enough test data to develop such a method for determining the long-term CFRP strap strains. Future research into long-term deflections should look at variables such as span to depth ratio and strap prestress to better understand the potential increases in strap strain and the relationship to shear deflection.

Fortunately, since most structures where this retrofitting technique would be employed will have already undergone substantial long-term creep deflection, significant increases in strap strain should not be an issue. The long-term test also considered the most severe loading case of a live load applied over a long period of time. Most structures are unlikely to see the full live load applied for significant periods of time and so increases in deflection and strap creep strains should be lower. Since this technique is not limited by the constraints of other FRP retrofitting techniques (bond, anchorage, and localized stress concentrations), the number of strap loops can be increased to reduce the strain required to obtain the same level of prestress and thus the total strain.

The long-term deflection test has further demonstrated the potential of these straps. The straps have not failed after approximately seven months under a load that exceeds the capacity of a unretrofitted RC beam of the same design by 25%. This bodes well for the future use of this CFRP strap retrofitting system.

CYCLIC LOADING TEST

Test Set-Up

The specimen used for the cyclic load test had the same design as that used in the long-term test so a comparison could be made between their performances. The shear force was cycled between 70 and 110kN in this test at a frequency of 2Hz as illustrated in

Figure 11. Ideally the shear force would have been cycled between 30 and 110kN to represent the 80kN fatigue vehicle specified in BS 5400. However, it was not possible to design a testing rig with the available equipment to accommodate such a large load differential. The current loading was deemed adequate as the lower limit of the loading range, 70kN, was below the capacity of the control specimen (88kN) whilst the upper limit, 110kN, was above this value. This loading range is perhaps also more realistic for many types of structures, where the dead load is a significant portion of the total load. Based on the strap strain readings from static tests, this load range creates a significant difference between minimum and maximum CFRP strap strains.

The testing rig was a self-reacting frame as illustrated in Figure 12. The specimen was placed on top of a steel beam, which served as the reaction beam. The reaction beam was then attached to specially made channel sections that were bolted to the columns. The columns supported the dynamic jack making the system completely self-contained preventing fatigue of the strong floor.

An Amsler testing machine capable of applying both a constant base load as well as a pulsating dynamic load was used. The applied load was measured using a 500kN load cell. Five LRDTs were used with one at each support, one at each load point, and one at the midpoint of the beam. Strain gauges were placed at the midpoint of the top and bottom longitudinal reinforcing bars. Gauges were also placed at the mid-height of each stirrup in one of the shear spans as well as on each CFRP strap. The results were monitored using a high-speed data acquisition system capable of scanning each data channel 100 times a second. The program was designed to record two seconds of data every hour so that changes with time could be measured.

<u>Cyclic Behaviour</u>

<u>Deflections</u> -- Although the beam will eventually be tested to two million cycles, only the results of the first million load cycles will be reported here. However, most of the trends are evident by this point in the testing. The maximum and minimum mid-span deflections are plotted against the number of cycles in Figure 13. The displacement increases over time, which is quite similar to the behaviour exhibited by the long-term specimen. The overall deflection increase factor of 1.15 is not nearly as significant as the 1.57 noted for the long-term test. However, the average load applied to the specimen is lower, at 90kN, than was used in the long-term test. This results in lower concrete stresses and reduced creep. The load is also applied over a much shorter time frame, further decreasing the amount of concrete creep and resulting deflections. Interestingly there is little change in the difference between maximum and minimum displacements over time. This indicates that for the given time, t, the beam stiffness over this load range remains relatively constant since a drop in stiffness would result in a larger change in the maximum displacement versus the minimum displacement. At the same time the overall beam stiffness is decreasing as the maximum and minimum displacements are increasing with time. This result suggests that the change in stiffness is a function of the constantly applied base load, and not the additional cyclic load.

There is a slight drop in the overall deflection at approximately 920000 cycles and then an increase thereafter. This corresponds to a period of 4 days when the beam had to be completely unloaded and realigned in the rig. The initial decrease in deflection is believed to be due to the cracks closing slightly while the beam was unloaded. An examination of the steel stirrup data over the same period showed that the strain in the stirrups had decreased in a similar fashion to the displacements, which also suggests that the crack widths decreased during the period of unloading.

The fatigue capacity of a composite beam is limited by the fatigue capacity of its component parts. As such, when considering whether to retrofit a structure, the designer must not only consider the fatigue capacity of the retrofitting material (the CFRP straps) but also the reinforcement and concrete in the existing beam.

<u>CFRP Straps</u> -- The strap strains are plotted against the number of cycles in Figure 14. Once again the shape of the plot is similar to the long-term tests, with the strains increasing with time. The strains in the middle straps have increased by a factor of 1.14, which is less than the 1.23 observed in the long-term tests. It suggests that in terms of a strain increase, a sustained long-term load is more critical. The difference between the minimum and maximum strain, and corresponding stress range, in the straps remains constant for the duration of the test. The middle straps have the largest stress range of approximately 85MPa. This constant stress range indicates that the cracks in the concrete are not growing significantly, which validates the conclusion that the stiffness over this loading range is also not changing significantly. Despite exhibiting slight increases in average strain, the straps appear to have the required fatigue capacity. However, even under the maximum load the stresses in the straps are only about 50% of the ultimate strap tensile capacity, so future work with higher average stresses and with higher stress ranges should be performed to validate this result.

<u>Reinforcement fatigue</u> -- The minimum stress level in the middle steel stirrups is approximately 275MPa whilst the maximum is 400MPa. This leads to a stress range of 125MPa, which is below the 280MPa that design codes (BS 5400 1996) deem to be acceptable. Tilly (1979) suggested that the fatigue properties of the reinforcement were dependant upon both the stress range and the average mean stress. For the case of the transverse reinforcement, the average mean stress is 338MPa, which is higher than the values tested by Tilly. He observed that increasing the average stress from 159MPa to 275MPa resulted in a 40MPa reduction in the stress range that caused failure at 10^6 cycles. The stress range to cause failure at an average stress of 275MPa was found to be approximately 210MPa. The data given by Tilly seems to exhibit fairly linear behaviour (although this requires confirmation) so by extrapolation another 40MPa reduction in stress range will occur between an average stress of 275MPa and 391MPa, making the stress range to cause failure 170MPa. As such, a fatigue failure in the transverse reinforcement should not be critical.

Unfortunately the strain gauges on the longitudinal reinforcement gave erroneous results during the cyclic test, which was probably due to loss of bond between the gauge and reinforcement bar. Results from previous static tests indicate that the minimum stress in the longitudinal reinforcement is approximately 310MPa with a maximum of approximately 475MPa at these load levels. This leads to a stress range of 165MPa, which is within the code limits of 220MPa for this bar diameter. However, when one considers the extrapolation of Tilly's work given above, the average stress of 393MPa results in a stress range of 170MPa to cause failure at 10^6 load cycles. This extrapolated stress range is quite close to the actual stress range, which suggests the possibility of a fatigue failure in the longitudinal reinforcement. If the full intended loading between 30 and 110kN had been used, then the stress would definitely have exceeded these limits. A method of predicting fatigue failure in the tensile reinforcement has been presented by Heffernan, Erki, and DuQuesnay (2004). Their method indicates that the stresses in the reinforcement need to be increased by a factor of 1.2 to allow for stress concentrations at the concrete cracks and a further 1.05 to account for tensile strain increases due to concrete softening. This would further reduce the potential stress range in the longitudinal reinforcement. Thus, any designer hoping to employ this shear retrofit system should give careful consideration to fatigue of the existing reinforcement as well as the straps.

Concrete fatigue -- Although not specifically investigated in this experiment, Czaderski and Motavalli (2004) also noted the importance of the concrete capacity. In their experiments on T-beams retrofitted with CFRP L-shaped plates, they were able to load the specimen between 39 and 59% of the ultimate specimen capacity for five million cycles. They noted that the concrete compression strain had increased significantly during the course of their test. As such, Czaderski and Motavalli recommend that the designer consider carefully whether there is enough remaining concrete capacity in the structure to be retrofitted.

Whilst the designer must exercise care when applying any retrofitting method, the cyclic testing has demonstrated the durability of the CFRP strap retrofitting system. The straps were used to strengthen a beam that was subjected to loads between 0.8 and 1.25 times its unretrofitted capacity for one million cycles without displaying any signs of fatigue failure.

CONCLUSIONS

The long-term test illustrated that the CFRP straps can provide significant shear enhancement over long periods of time. Nevertheless, the designer must be aware of the possibility of increases in strap strains as the RC beam creeps. The increases in strap strain can potentially be estimated and taken into account in the design of the strengthening system. Furthermore, the strain increases should be relatively small due to the level of loading and extent of creep in existing structures. The development of a database of long-term deflections due to flexure and shear is also required.

The cyclic load tests also indicated that the CFRP strap system has the required capacity to provide long-term shear enhancement. The increases in both deflection and strap strains were not as significant as for the long-term load test. As such, the long-term load would appear to be more critical in terms of strap strain and deflections. The designer also needs to consider the fatigue capacity of the existing structure, as it is possible that increased load levels could cause fatigue failure of the internal steel longitudinal reinforcement or concrete.

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REFERENCES

ACI Committee 318, 1995, *Building code requirements for structural concrete*, American Concrete Institute, Farmington Hills, MI.

ACI Committee 435, 2003, *Control of Deflection in Concrete Structures (Appendix B)*, American Concrete Institute, Farmington Hills, MI, pp. B1-B13.

BS 5400, 1980, *Steel, concrete and composite bridges Part 10. Code of practice for fatigue*, British Standards Institution, London, England.

BS 5400, 1996, *Amendments to BS 5400: Part 4:1990*, British Standards Institution, London, England, 4 pp.

Collins, M.P., and Mitchell, D., 1997, *Prestressed Concrete Structures*, Response Publications, Toronto, 766 pp.

Czaderski, C. and Motavalli, M., 2004, "Fatigue behaviour of CFRP L-shaped plates for shear strengthening of RC T-beams," Composites Part B: Engineering, V. 35, No. 4, pp. 279-290.

De Lorenzis, L. and Nanni, A., 2001, "Shear Strengthening of Reinforced Concrete Beams with Near-Surface Mounted Fiber-Reinforced Polymer Rods," ACI Structural Journal, V. 98, No. 1, pp. 60-68.

Espion, B. and Halleux, P., 1990, "Long-Term Deflections of Reinforced Concrete Beams: Reconsideration of Their Variability," ACI Structural Journal, V. 87, No. 2, pp. 232-236.

Heffernan, P.J., Erki, M-A. and DuQuesnay, D.L, 2004, "Stress Redistribution in Cyclically Loaded Reinforced Concrete Beams," ACI Structural Journal, V. 101, No. 2, pp. 261-268.

Hoult, N.A., and Lees, J.M., 2004, "Shear Retrofitting of Reinforced Concrete Beams Using CFRP Straps," Proceedings of the 4th International Conference on Advanced Composites in Bridges and Structures, Calgary, Canada, 2004, 8 pp.

Kani, M.W., Huggins, M.W. and Wittkopp, R.R., 1979, *Kani on Shear in Reinforced Concrete*, Department of Civil Engineering, University of Toronto, 226 pp.

Kesse, G. Chan, C. and Lees, J., 2001, “Non-linear Finite Element Analysis of RC Beams Prestressed with CFRP Straps,” *FRPRCS-5*, Thomas Telford, Cambridge, England, Vol. 1, pp. 281-290.

Kesse,G., 2003, *Concrete Beams with External Prestressed Carbon FRP Shear Reinforcement*, PhD Thesis, Department of Engineering, University of Cambridge, 222 pp.

Nie, J. and Cai, C.S., 2000, “Deflection of Cracked RC Beams under Sustained Loading,” Journal of Structural Engineering, Vol. 126, No. 6, pp. 708-716.

PCI, 2003, “ACI releases second edition of ‘Concrete Repair Manual',” Concrete Monthly, http://concretemonthly.com/monthly/art.php/105, accessed on February 15, 2005.

Saadatmanesh, H. and Tannous, F.E., 1999, “Relaxation, Creep, and Fatigue Behavior of Carbon Fiber Reinforced Plastic Tendons,” ACI Materials J., V. 96, No. 2, pp. 143-153.

Stenger, F., 2003, “Tragverhalten von Stahlbetonscheiben mit vorgespannter externer Schubbewehrung aus Kohlenstofffasern,” *CFK im Bauwesaen – heute Realitat!*, EMPA Akademie, Dubendorf, Switzerland, pp. 59-67.

Tilly, G.P., 1979, “Fatigue of Steel Reinforcement Bars in Concrete: A Review,” Fatigue of Engineering Materials and Structures, Vol. 2, pp. 251-268.

Triantafillou, T.C., 1998, “Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites,” ACI Structural Journal, Vol. 95, No. 2, pp. 107-115.

Winistoerfer, A.U., 1999, *Development of non-laminated advanced composite straps for civil engineering applications*, PhD Thesis, Department of Engineering, University of Warwick, 170 pp.

Table 1 – Steel reinforcement properties

Bar Diameter (mm)	Yield Strength (MPa)	Yield Strain	Elastic Modulus (GPa)	Ultimate Strength (MPa)
6	578* ± 5	0.00501*	187.4 ± 6.8	646 ± 0
8	467 ± 6	0.00233	200.3 ± 3.2	540 ± 5
16	505 ± 7	0.00262	192.9 ± 13.3	586 ± 5
20	523 ± 2	0.00263	198.7 ± 6.5	633 ± 1

- using the 0.2% offset method

Table 2 – Concrete strengths

Specimen	Compressive Cube Strength (MPa)	Split Cylinder Strength (MPa)
Long-term load	42.9 ± 1.5	2.7 ± 0.9
Cyclic load	42.2 ± 1.7	3.0 ± 0.1

Table 3 – CFRP strap properties

Modulus of Elasticity (GPa)	Ultimate Strain (mm/mm)*	Experimental Tensile Capacity (kN)**
121.0 ± 4.7	0.01	59.3 ± 2.3

* based on tests performed by Winistoerfer (1999)

** based on the average results of the 10 loop tests using the steel support pads

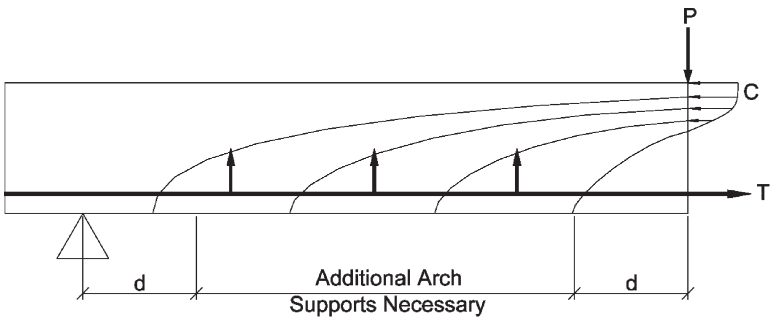

Figure 1 – Kani arch model

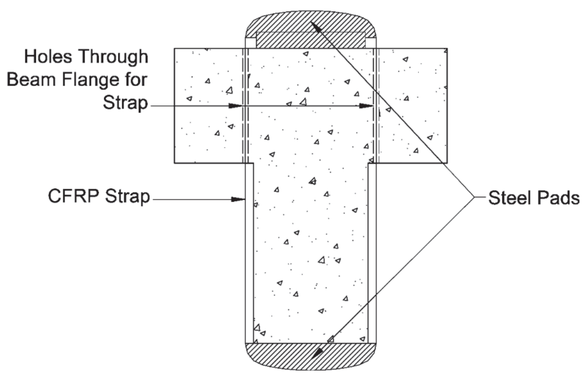

Figure 2 – CFRP strap configuration used in Kesse, Chan and Lees

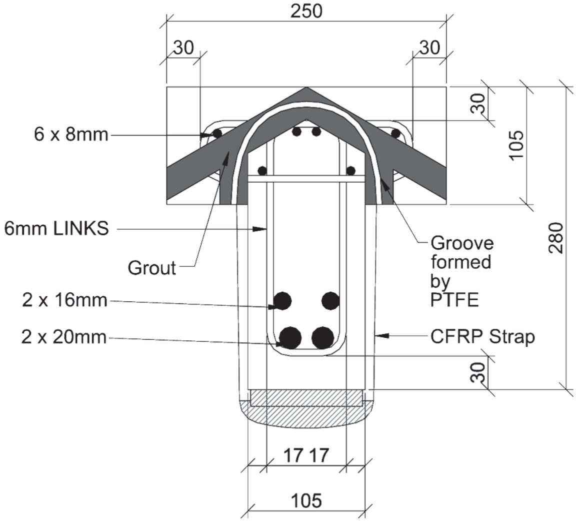

Figure 3 – Beam cross-section

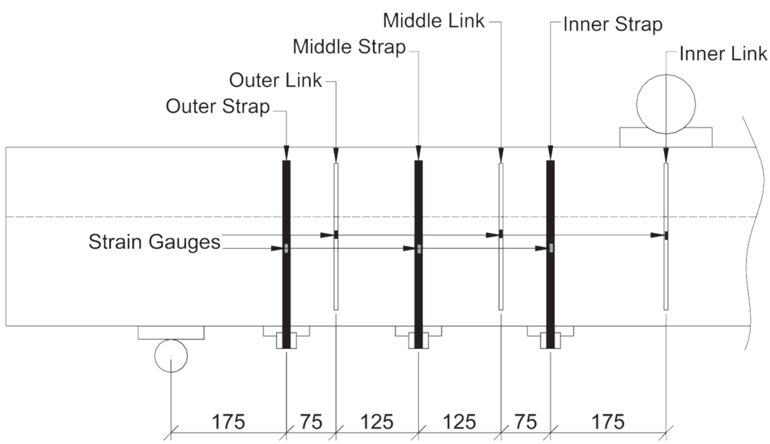

Figure 4 – Strap layout

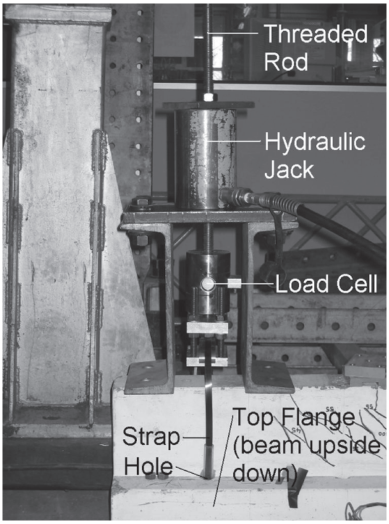

Figure 5 – Strap prestressing system

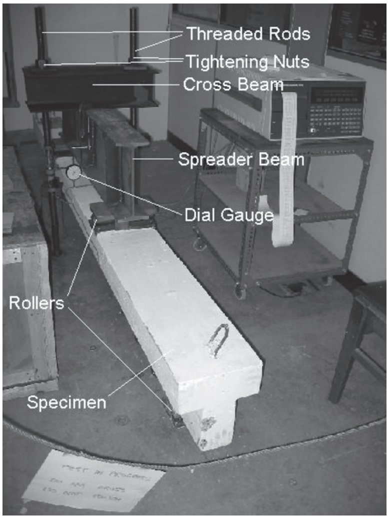

Figure 6 – Long-term beam test set-up

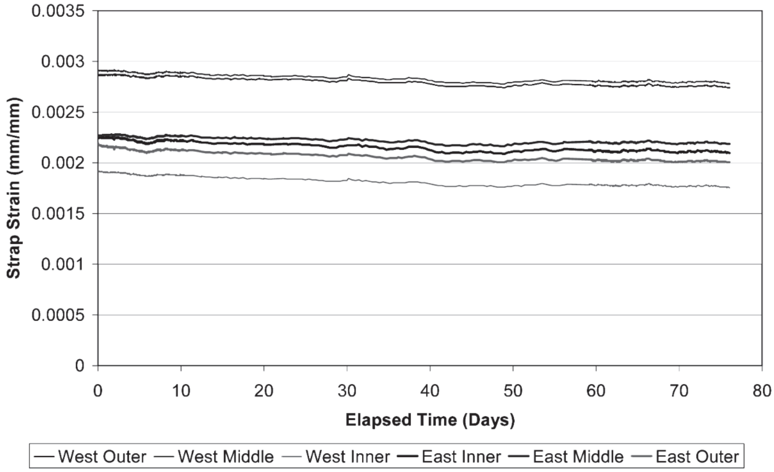

Figure 7 – Long-term CFRP strap strain vs. time under no applied load

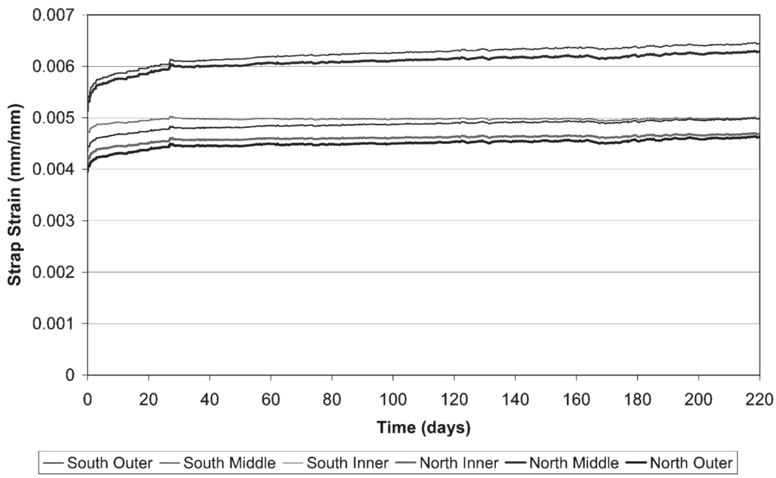

Figure 8 – Long-term CFRP strap strain vs. time under applied load

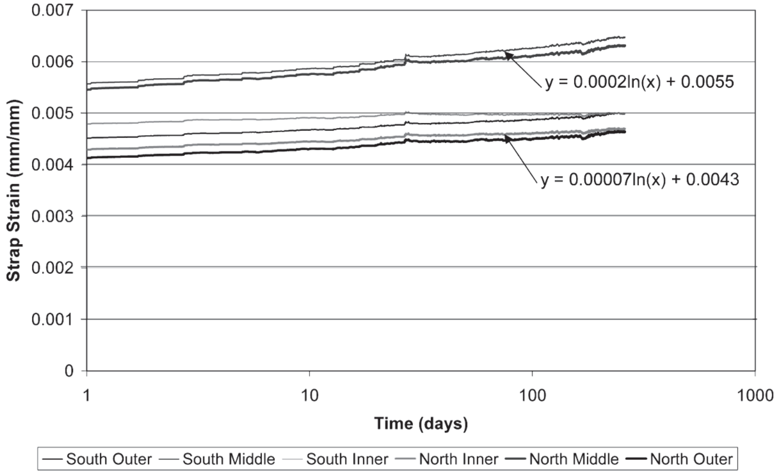

Figure 9 – Logarithmic plot of strap strain vs. time

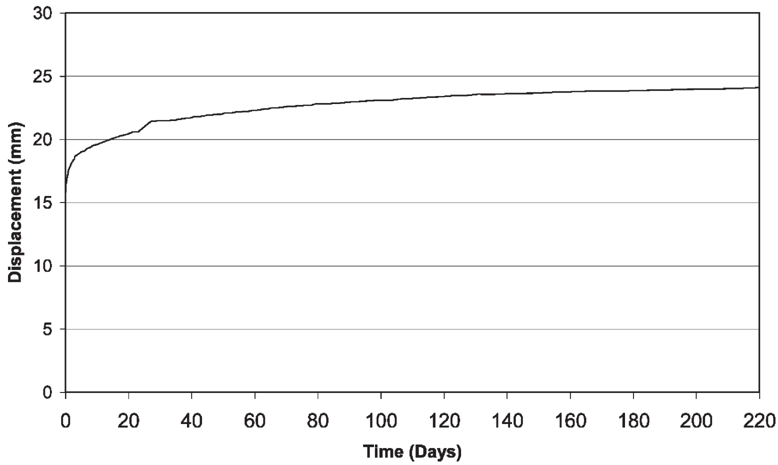

Figure 10 – Long-term midspan deflection vs. time

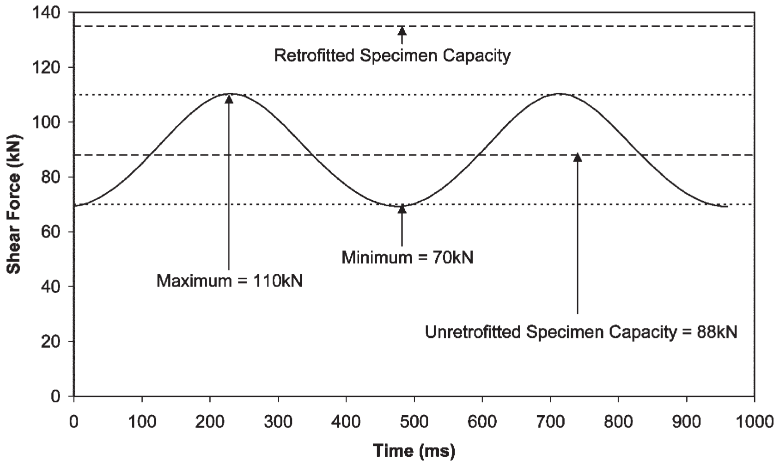

Figure 11 – Cyclic Loading

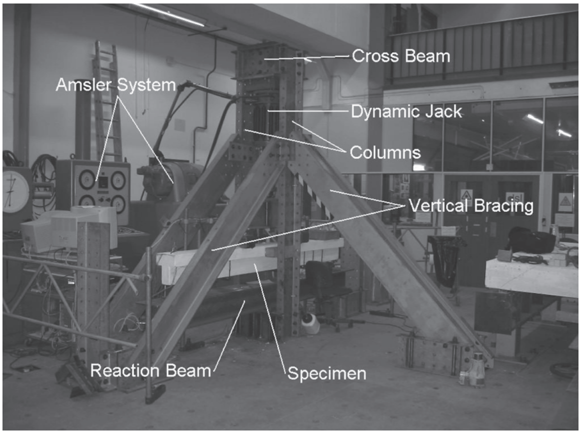

Figure 12 – Self-reacting frame for cyclic test

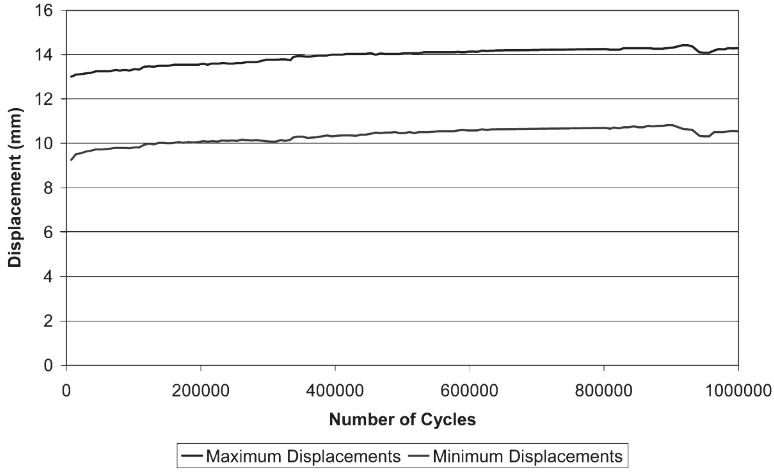

Figure 13 – Mid-span deflection vs. number of cycles

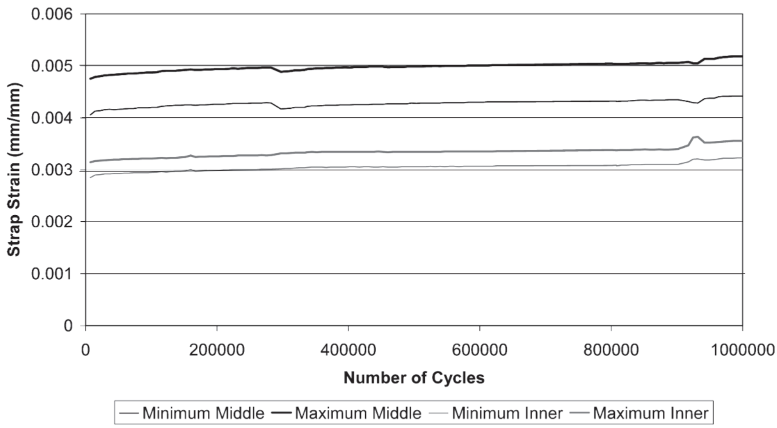

Figure 14 – Strap strains vs. number of cycles