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Efficient CFRP Strap Configurations for the Shear Strengthening of RC T-beams

Neil A. Hoult[1] and Janet M. Lees[2]

Abstract: A prestressed carbon fiber reinforced polymer (CFRP) strap retrofitting system has been found to significantly enhance the shear capacity of existing reinforced concrete (RC) beams. In previous studies, the CFRP straps were supported on metal pads placed on the top and bottom of a beam necessitating top surface access. The goal of the current work was to develop a system where the straps were installed from underneath a slab without compromising the strengthening efficiency. A series of T-beam experiments was conducted where the CFRP straps were inserted through holes that were drilled from below the flange thereby avoiding the need for access to the top surface. The depth of penetration of the CFRP straps into the compression flange, the concrete strength, the CFRP strap spacing, the presence of holes in the compression flange, and the size of the loading pads were all found to affect the shear performance. Using the most successful installation technique, the resulting CFRP strengthened beam failed at a load that was approximately 50% higher than that of an unretrofitted control beam.

CE Database subject headings: Fiber reinforced polymers, Shear, Concrete beams

[1] Research Associate, Department of Engineering, University of Cambridge, Trumpington St., Cambridge, UK, CB2 1PZ. E-mail: neil.hoult@gmail.com
[2] University Senior Lecturer, Department of Engineering, University of Cambridge, Trumpington St., Cambridge, UK, CB2 1PZ. E-mail: jmL2@eng.cam.ac.uk

Introduction

An increasing number of existing reinforced concrete structures are being found to have insufficient shear capacity. There are several possible reasons for these deficiencies including more conservative design codes, increased loading requirements, and reductions in the capacity due to the corrosion of the internal steel reinforcement. When faced with these problems facility owners have three options: impose load restrictions, strengthen the structure or rebuild the structure. From a sustainability and economic perspective, the possibility of increasing the capacity of existing structures in a cost-effective manner is an appealing option.

A particular challenge in the design of shear strengthening systems for existing structures is the trade-off between the strengthening efficiency and practical constraints. In fundamental shear theories, the shear contribution of the transverse reinforcement comes from the transfer of force between the tension and compression zones. However, in most types of construction, such as T-beams and beam-on-slab, the compression zone is not easily reached and thus cannot be easily tied to the tension zone using retrofitting techniques. Consider the case where a beam-on-slab structure is to be strengthened. Whereas the sides of the beams may be fairly accessible, access to the top surface of the slab to install a strengthening system that ties the tension and compression zones together can be more difficult. The need for top slab access may not always be a concern; however, there are applications where such an access requirement would be detrimental. For example, closing a highway bridge for the required retrofitting and road resurfacing could have a major economic impact in terms of delay times.

The addition of external fiber reinforced polymer (FRP) reinforcement to an existing structure is one possible retrofitting technique for enhancing the shear capacity of a RC beam. FRP-based strengthening techniques have several advantages over traditional steel retrofits since FRPs have high strength-to-weight ratios and are corrosion resistant. A considerable amount of work has been undertaken in the past decade to investigate FRP shear retrofitting of RC beams, and this research has primarily focused on the use of FRP sheets or fabrics that are epoxy bonded to the surface of the concrete. For a bonded FRP system, one way to avoid top slab access is to only apply the FRP sheets to the sides and base of the beam (often referred to as a ‘U’ wrap).

However, in such a case the strengthening efficiency will be compromised for several reasons. First, when used on T-beams or slab-on-beam construction because the FRPs are only applied to the sides and bottom of the specimen, they will not effectively tie the compression zone to the tension zone which is crucial for carrying shear as noted earlier. Secondly, when the FRPs are bonded only to the sides of a beam or in a 'U' configuration, the bond between the concrete and the FRP as well as the FRP development length often limits the capacity enhancement provided by these techniques (Triantafillou 1998; Adhikary *et al.* 2003). And indeed experiments on epoxy bonded CFRP strengthened beams (Adhikary *et al.* 2003; Melo *et al.* 2003) have shown that beams strengthened in a 'U' configuration can exhibit a lower level of shear enhancement than equivalent fully wrapped beams.

The current research investigates the use of a novel CFRP strap retrofitting system developed by Winistoerfer (1999). The system uses unidirectional CFRP fibres in a nylon thermoplastic matrix that form 12 mm wide by 0.16 mm thick tapes. These tapes can then be wrapped around a beam section as illustrated in **Fig. 1** to form closed straps that provide additional external shear reinforcement (in the case of a T-beam with top slab access, vertical holes would be drilled through the flange). The outermost tape layer is welded to the next outermost layer by fusion bonding the thermoplastic matrices of the two layers together. This weld creates a closed outer loop (a loop being one complete revolution of the tape around the beam), which the inner loops then tighten against. Because the tape is continuous, the number of loops can be varied based on the required capacity. Each loop then shares the load, and for the tape used in the current work adds a contribution of approximately 5 kN to the load carrying capacity of the strap. A further advantage is that the straps can be prestressed with an initial load, which can have beneficial effects on the total shear force that a beam can carry (Stenger 2000). The system requires the use of relatively small quantities of CFRP. Also, the welding procedure only takes approximately 10 minutes so the straps are ready to take load quickly, whereas in bonded FRP systems the epoxy takes several days to set completely. Hence, a strap system could be installed quickly, allowing a structure to be fully strengthened over the course of a weekend when traffic demand and delay costs are lower.

In terms of performance, as these straps are not bonded to the surface of the beam and are self-anchored, unlike bonded systems, debonding and development length issues do not arise. However, the trade-off between strengthening efficiency and practical installation issues remains. As originally developed, the system relied on support pads on the top and bottom surfaces of a beam to transfer the tensile forces from the straps to the beam. The presence of a bottom support pad will have implications on design considerations such as headroom but is not thought to be a major obstacle. However, as discussed, there are applications where the requirement for top slab access would be detrimental and being able to install the CFRP retrofit from under the slab is appealing. To take advantage of the closed loop nature of the strap system, under-slab installation will require drilling so the strap can encompass the beam web. In terms of ease of installation, drilling a horizontal hole straight through the web just below the junction with the flange would be desirable but then the strap would not be anchored in the compression zone and the shear capacity enhancement would be adversely affected. It is important to note that holes would be required for *any* shear retrofitting system, FRP or steel, to properly engage the compression flange of a T-beam or slab-on-beam structure.

The current experimental program seeks to investigate both installation and strength enhancement considerations. In particular, the goal was to develop a technique for installing these CFRP straps in T-beam or slab-on-beam structures that would offer shear enhancement equivalent to that provided by fully enclosing the section, but would not require access to the top surface of the beam. The chosen technique would limit the damage to the top surfacing layer and potentially make it possible to carry out the repairs without closing the facility.

The following sections outline previous research undertaken using these CFRP straps and the development of the under-slab CFRP strap retrofitting system. The impact of transverse reinforcement penetration into the compression flange on the overall shear strength of the beams and the influence of the concrete strength and CFRP strap spacing will be examined. In addition, two experimental issues, connected to the size of the bearing pads and the size of holes in the compression flange required to install the straps, will be discussed in greater depth.

Previous Research

Previous research has been conducted using the CFRP straps to strengthen reinforced concrete T-beams (Kesse *et al.* 2001; Lees *et al.* 2002), rectangular sections (Kesse 2003; Kesse and Lees 2007), and deep beams (Stenger 2000). Kesse *et al*. (2001) tested two T-beams: an unstrengthened control specimen and a retrofitted specimen (in this case the CFRP straps were supported on metal pads on both the top and bottom of the specimen). They found that while the control beam failed in shear at 100 kN, the retrofitted specimen's load carrying capacity increased by 48% and the failure mode changed from shear to flexure. One of the most extensive research programs conducted using the strap system investigated the effect of strap spacing, strap stiffness, and level of prestressing force in the strap on the shear capacity of rectangular RC beams (Kesse 2003). Kesse (2003) found that in order to achieve a flexural failure in initially shear-deficient beams, the maximum strap spacing should be no more than the effective depth of the beam, *d*. He also determined that there was a minimum level of strap stiffness and tensile capacity that was required to force a flexural failure. Beams with only five loops of CFRP tape failed in shear, whereas some of the beams with 10 loops exhibited ductile flexural failures. If the strap capacity and spacing were adequate, the level of prestress did not seem to matter significantly, as long as it was above a minimum value dictated by the section geometry and the strap stiffness. However, the influence of the prestress level is dependant on the size of the section, as Stenger (2000) found that prestress played a key role in any strength enhancement provided to deep beams.

Experimental Investigation

Specimens

The seven specimens tested in the current study had a T-beam cross section similar to that used by Kesse *et al*. (2001), the dimensions of which are illustrated in **Fig. 1**. The reinforcement properties are given in **Table 1.** To reflect a shear-capacity deficient beam, nominal internal steel stirrups were incorporated using 6 mm diameter plain steel bars placed at 250mm spacing. The advantages of using this particular beam cross-section and reinforcement layout were two-fold. First, the difference between the shear and flexural capacity of the unretrofitted section was approximately 50%, allowing one to gauge the effectiveness of the retrofitting technique.

Second, since the goal of the research was to develop an under-slab installation technique, this cross-section served as a realistic representation of slab-on-beam construction.

In considering possible ways of installing the CFRP straps from below, it was felt that drilling intersecting straight holes through the concrete would be the most practical approach. Care would need to be taken to avoid any existing internal steel reinforcement. In practice this could be achieved with reference to the design drawings and the use of a covermeter. By employing a rig to hold the drill it was found to be straightforward to drill intersecting holes into the flange. The size of the holes was dictated by the width of the strap and also the need to support the strap. Tests on the CFRP straps (Hoult 2005) indicated that it was inadvisable to have the strap bear directly on the drilled concrete profile since the sharp edges of the concrete damaged the strap and the transverse curvature of the cylindrical hole reduced the strap capacity. Two methods of supporting the strap were therefore considered. In the first method, profiled metallic inserts with a flat bearing surface were inserted in the hole. In the second method, the desired strap profile was formed within the concrete or grout placed in the hole.

Fig. 2 illustrates the strap configuration used in each specimen cross-section. The beam designation is denoted as AA/BB/C/DD for all specimens except the unstrengthened control beam which is referred to as B1/25; AA is the beam number, BB gives the angle of the holes (required for the straps), C indicates whether the holes were left open with metallic support inserts (H), grouted (G), or filled with concrete (C). Finally, DD is the nominal concrete cube strength.

As discussed in the introduction, there is often a contradiction between the installation and capacity enhancement requirements. The most straightforward method of installing the CFRP straps from underneath the slab would have been to drill a hole just below the flange horizontally across the web of the beam and then pass the tape through this hole to form loops. However, in order to achieve significant increases in shear capacity the shear reinforcement must tie the tension and compression flanges of the beam together. As such, the installation technique for specimen B2/45/H/20 used two 45° holes as illustrated in **Fig. 2(a)** in order to ensure the CFRP straps extended into the compression flange while at the same time minimizing the amount of drilling required. Profiled steel inserts were inserted in the holes to support the strap. For specimen B3/30/H/22 a more complex hole pattern was used as illustrated in **Fig. 2(b)** so that the straps could encompass almost the full depth of the beam. Again, the straps were supported on steel inserts. Specimens B4/30/G/25 and B7/30/G/36 used the same hole pattern as B3/30/H/22 but in this case the holes were grouted. In order to grout the holes after they were drilled, a strip of polytetrafluoroethylene (PTFE) was placed in them to serve as a form for the groove illustrated in **Fig. 2(c)**. A concrete repair material (referred to hereafter as grout) was then placed in the holes with the aid of vibration. Once the grout had hardened the PTFE strip was removed and the CFRP straps could be installed. To determine whether material incompatibilities between the grout and the original concrete affected the beam capacity, two specimens where the grooves for the CFRP straps were cast directly into the concrete were also tested for comparison purposes (B5/30/C/27 and B6/30/C/44, see **Fig. 2(d))**.

The CFRP straps consisted of 10 loops, as this was found to be an effective configuration to achieve a flexural failure for this T-beam geometry when metal pads were used on the top and bottom of the beam by Kesse *et al.* (2001). The CFRP straps had a cross-sectional area of 38.4 mm^2 and a modulus of elasticity of 121 GPa (Winistoerfor 1999). The capacity of the 10 loop strap was determined experimentally to be 59.3 kN resulting in an ultimate stress of 1544 MPa and a rupture strain of 0.0127. The bottom strap support pad was the same in all cases. The straps were prestressed to approximately 15kN per strap (25% of the ultimate strap capacity), which was determined through the use of a load cell in the prestressing rig. For specimens B2/45/H/20 through B6/30/C/44 the strap spacing was 250 mm as seen in **Fig. 3**. For specimen B7/30/G/36 the strap spacing was reduced to 200mm to investigate load sharing between the straps.

Test Set-up

The beams were tested in four-point bending as shown in **Fig. 4**. The load was applied with two hydraulic jacks. For specimens B1 through B5, the loading pads under the jacks were 100 mm by 100mm, which was the same width as the web of the beam. For specimens B6 and B7, the size of the loading pads was increased to 140 mm long by 250 mm wide (the same width as the flange of the beam) for reasons discussed later. Deflections were measured using 11 linear variable resistance transducers (LVRTs) spaced at 250 mm along the beam. Strain gauges were also placed at the mid-height of the internal steel stirrups, at the midpoint of the longitudinal reinforcement, and at the mid-height of the CFRP straps.

Experimental Results

The shear force versus mid-span deflection results for the seven T-beam tests are shown in **Fig. 5**. The maximum shear force attained by each specimen as well as the concrete cube compressive strength, percentage increase in capacity, the maximum mid-span deflection and the failure modes are given in **Table 2**. The maximum mid-span deflection is taken as the maximum deflection measured while the applied shear force was still within 5% of the maximum shear force. Thus for a ductile specimen, the tabulated value represents the maximum deflection attained on the plateau of the load-deflection curve. For comparison purposes the capacities of the two specimens tested by Kesse *et al.* (2001) have also been included, C1/50 was the control specimen and C2/45 was the retrofitted specimen where the CFRP straps were installed using support pads on the top and bottom of the beam, as they offer an insight into the influence of higher concrete strength.

All seven beams initially had approximately identical stiffness. However, the stiffness of the beams began to diverge at approximately 40 kN as seen in **Fig. 6**. This was to be expected since shear cracks began to appear at this load and so the deflection was now the result of a flexural and a shear component. The control specimen (B1/25) had the largest reduction in stiffness after cracking due to the absence of any additional CFRP shear reinforcement to minimize crack openings and thus reduce deflections. The deflection of reinforced concrete beams is often calculated based exclusively on flexural effects but the difference in the post-cracked stiffness of the unstrengthened and strengthened beams with similar concrete strengths demonstrates that shear effects play a role.

The unstrengthened control specimen (B1/25) failed in shear at a force of 88 kN. As can be seen from **Fig. 6** the failure was quite brittle. Despite the presence of the CFRP straps installed in ungrouted 45° holes, the first retrofitted specimen (B2/45/H/20) failed in shear at a maximum load of 95.4 kN which was only a small increase over the unstrengthened capacity. The failure of the strengthened specimen with ungrouted 30° holes (B3/30/H/22) at an even lower load of 91 kN was a surprising result since this specimen had a greater depth of strap penetration in to the flange than the ungrouted 45° specimen (B2/45/H/20). This suggested that the ungrouted holes played a role in the failure of the specimen as will be discussed later. The capacity of the specimen with the 30° grouted holes (B4/30/G/25) was 105 kN, which represented a 15% increase over the specimen with unfilled holes and indicated that filling the holes increased the capacity. Horizontal cracks were observed to have developed next to the grouted holes, suggesting the possibility of material incompatibility between the grout and the surrounding concrete. However, this material incompatibility was found not to be significant since a specimen where the grooves for the CFRP straps were cast into the concrete (B5/30/C/27) failed in shear at a similar load of 110 kN, and so any grout/concrete incompatibility was eliminated. It seemed that both B4/30/G/25 and B5/30/C/27 failed due a localized bearing problem in the area of the loading pad as will be discussed in greater detail in the Experimental Issues section. A specimen with a higher concrete strength, grooves for the straps cast into the concrete and wider bearing pads (B6/30/C/44) also failed in shear at 141 kN but the capacity was 59% higher than the low strength concrete control specimen (B1/25) and 41% higher than the higher strength concrete control specimen (C2/50). Finally, a specimen with a slightly smaller strap spacing where the straps were installed in a practical manner by placing them in holes that had been drilled and then filled with grout (B7/30/G/36) failed in flexure at 135 kN due to crushing of the concrete after the longitudinal reinforcement yielded in the maximum moment region of the beam. The yielding of the reinforcement was confirmed by the strain gauge readings on the longitudinal steel and, as a result of this failure mode, this specimen exhibited more ductility as illustrated in **Fig. 5**. Because of the difference between the concrete strength of the control specimen, B1/25, and specimen B7/30/G/36 (25 MPa versus 36 MPa) the percentage increase in capacity will be slightly different than for two specimens with the same concrete strength. However, a similar increase in capacity was noted between specimens C1/50 and C2/45 which had comparable concrete strengths indicating that the capacity enhancement achieved in the current test series is quite realistic despite the variation in concrete strength.

It should be noted that none of the CFRP straps failed during these experiments. Earlier research by Kesse (2003) investigated the effect of varying the number of strap loops by testing specimens where strap failure governed; hence there exists an empirical understanding of how many loops are required to achieve a given capacity. Furthermore, the additional cost of adding extra loops to ensure the straps do not fail is expected to be insignificant when compared with labour costs; thus the strengthening system was designed so that a strap failure was not anticipated.

Discussion

The increase in shear force carrying capacity and ductile flexural failure achieved using the CFRP strap retrofitting system installed from underneath a T-beam demonstrates the potential of the system. However, the experimental results indicate that when developing a practical and efficient strap retrofitting scheme careful consideration should be given to the penetration of the transverse reinforcement into the flange of the beam, the concrete strength of the element to be retrofitted and the CFRP strap spacing. Each of these factors can affect the overall specimen capacity, failure mode and ductility of the specimen as discussed in the following section.

Design Considerations

The depth to which the CFRP straps extend into the compression flange appears to affect the shear capacity of the specimens as can be seen by comparing the control specimen (B1/25), the specimen with 45° holes (B2/45/H/20) and a specimen with 30° holes (B4/30/G/25), all of which had similar concrete strengths but varying degrees of CFRP strap penetration into the compressive flange. In the case of the specimen with the 45° holes there are actually two potential strap installation issues that could affect the shear capacity: the role of the holes in the flange and the depth of penetration into the flange. It is believed that the premature cracking caused by the holes (as discussed in the Experimental Considerations section) was minimal in this specimen because the holes did not extend significantly into the compressive region. Hence the differences in behaviour between the specimen with 45° holes (B2/45/H/20) and 30° holes (B4/30/G/25) was assumed to be primarily due to the amount of the compression flange that was encompassed. This assumption can be further supported by comparing the failure modes of this specimen (B2/45/H/20) with the control specimen in **Fig. 6**. Both specimens had almost identical crack patterns with the crack in the flange forming at similar angles in both cases despite the fact that the control specimen had no holes in the flange. This qualitative evidence indicates that the straps simply did not reach high enough into the flange of the beam with the 45° holes to restrain the main shear cracks, resulting in an almost identical failure mode to the control specimen. The CFRP strap strain data shown in **Figs 7** and **8** is also indicative of this phenomenon. In these figures, the increase in strap strain with increasing load is plotted (in order to determine the total strap strain, it is necessary to add the initial strap prestrain (0.003) to these values). The middle strap strains for the beam with 45° holes (B2/45/H/20) as seen in **Fig. 7** were the lowest for any beam at a given load. The inner strap strain data presented in **Fig. 8** is even more conclusive. In this case the strap strain never increased above the level of the prestressing strain suggesting that the strap never carried additional force. These results indicate that the depth of penetration has a significant effect on shear capacity. Kani *et al*. (1979) suggest that RC beams act as a series of nested arches that are tied together by the transverse reinforcement. The depth over which the transverse reinforcement acts will therefore be important to properly tie the arches together and develop the full shear capacity. This illustrates the need for drilling holes that penetrate sufficiently into the compression flange in order to gain the maximum possible contribution from the CFRP straps.

Once the straps are properly extended into the compressive flange the shear force is carried between the concrete, the internal steel stirrups and the external CFRP straps. How much load is carried by each element was found to be a function of the concrete strength as well as the CFRP strap spacing. The role of concrete strength is best illustrated by comparing two specimens with similar CFRP strap detailing in terms of spacing and penetration into the compressive flange but different concrete strengths: 27MPa (B5/30/C/27) versus 44MPa (B6/30/C/44). Although specimen B5/30/C/27 is believed to have failed prematurely due to a localized failure in the area of the bearing pad (as will be discussed in the Experimental Considerations section), its performance prior to failure provides a useful comparison. As illustrated in **Fig. 7**, the middle strap strains for the lower strength concrete specimen are higher at a given load as compared to the specimen with the higher concrete strength. Prior to failure the middle strap strains of the lower concrete strength specimen are twice as high as those for the higher concrete strength specimen. This result correlates well with shear models that suggest aggregate interlock is the primary shear force carrying mechanism in the concrete such as the Modified Compression Field Theory (MCFT) (Vecchio and Collins 1986). In the MCFT, the shear stress transferred along a crack, the concrete strength and the crack width are interrelated. Based on this, at a given shear force, a beam with a lower concrete strength would have larger crack widths, which would in turn result in larger strains in the CFRP straps since the strain in the unbonded strap is a function of the integrated crack widths at the strap location divided by the strap length. Unlike steel, CFRP does not yield and is a brittle material. As the strap strain depends on the concrete strength, it is important that this is reflected in the development of design equations for the strap system in order to avoid an unexpected strap failure.

The previous beam comparison suggests that the concrete strength influences the strap strain. However, there appears to be a contradiction in **Fig. 7** since, at a given load, the middle strap strain for beam B6/30/C/44 with a concrete strength of 44MPa was similar to that of B7/30/G/36 with a concrete strength of 36MPa. The only other difference between these two beams was the CFRP strap spacing which was 250mm (B6/30/C/44) and 200mm (B7/30/G/36). This would indicate that the strap spacing also influences the load sharing. It is observed from **Fig. 8** that the strains in the inner straps at a given load are greater for the specimen with the smaller strap spacing (similar behaviour was also demonstrated by the outer straps), and so the overall strap contribution at a given load for the weaker strength concrete specimen is greater. Thus the load sharing in the straps is affected by the strap spacing. Interestingly, it was the specimen with the lower concrete strength and smaller strap spacing (B7/30/G/36) that failed in flexure with a far more ductile failure mode. In this case, the combination of concrete strength and strap spacing was able to provide enough additional shear capacity to this specimen to force a flexural failure. These comparisons have illustrated the need to be able to accurately model both the affect of concrete strength and strap spacing in order to correctly determine the load sharing between the concrete, CFRP straps and steel shear links in order to correctly predict both the specimen capacity and failure mode.

Experimental Issues

During the course of the beam tests two issues relating to the specimen configuration were identified as having an impact on the overall capacity. Both the width of the bearing pad used to apply the point loads and the area of the holes used for strap installation affected the capacity.

There was a marked difference in the crack failure pattern near the load point between beams B4/30/G/25 and B6/30/C/44 even though the beams were nominally identical except for different concrete strengths and the width of the loading pads used to apply the point loads. As illustrated in **Fig. 9** the shear crack in specimen B6/30/C/44, where the bearing pad was the width of the beam flange, runs to the bearing pad but not beyond it. In contrast, the cracks in specimen B4/30/G/25, with a bearing pad the same width as the beam web, appear to form around the bearing pad. It seems a premature bearing problem potentially led to the failure of beam B4/30/G/25. At the peak load, the calculated bearing stress under the pad of B4/30/G/25 was approximately 10.5 MPa which was below the anticipated bearing capacity of 17 MPa assuming the bearing capacity is equal to 0.85 $f_c^{'}$. This suggests that the failure mode of beam B4/30/G/25 is rather more complex than a simple bearing failure and that the shear stresses also affected the capacity. While it is beyond the scope of this paper to analyse this complex failure mode in detail, it seems that the choice of bearing pad width has affected the failure mode of the beams and potentially resulted in a lower capacity. Although in practice loads are not applied with bearing pads, investigators conducting laboratory work should be aware that careful consideration needs to be given to the bearing pad in order to ensure the correct variables are being tested.

However, the size of the loading pad did not seem to have a significant effect on the capacity of the control beam. When compared to C1/50 which employed loading pads that were the full width of the flange and had a higher concrete strength (50 MPa), the failure loads (88 kN for B1/25 versus 100 kN for C1/50) as well as the crack patterns and failure modes were quite similar. This was believed to be due to the fact that the crack angle in the flange was much shallower (approximately 15º) than for the other specimens. Thus the control specimen (B1/25) does provide an accurate base reading for comparison despite the use of a smaller bearing pad.

The presence of ungrouted holes in the flange had a significant impact on the shear capacity as a beam with unfilled holes (B3/30/H/22) failed at a load 15% lower than its grouted counterpart (B4/30/G/25). It was observed that the shear cracks went directly through the unfilled holes and followed the inclined profile of the holes. This indicates that the holes actually serve as crack inducers, causing shear cracks to develop in the flange at much lower loads than would be the case if the holes were not there. This assumption correlates well with the elastic solution to the problem of a circular hole in a continuous medium which was first developed by Kirsch (1898). Kirsch's formulation suggests that the tensile stresses that develop perpendicular to the direction of applied compressive stress at the edge of the holes are equal to the applied compressive stress. As such, one can expect cracks to develop next to the holes once the applied compressive stress exceeds the tensile capacity of the concrete. In the case of the T-beam specimens with ungrouted holes, cracks would form in the flange with the same orientation as the anticipated shear cracks at loads well below those at which shear cracks should develop. These cracks in the flange then connect with the shear cracks in the web to cause premature failure of the specimen. This emphasizes the need to fill the holes with grout, to minimize the size of the holes, and, as much as is possible, to drill holes in the flange with an orientation as close to the vertical axis as possible in order to prevent premature shear failures.

Based on this experimental program, the following recommendations can be made about the installation and use of CFRP straps for retrofitting: if the straps are to be installed from under the slab, a hole pattern that ties the compression and tension flanges of the beam together is required to optimize the level of enhancement. These holes must then be grouted in order to ensure that a shear failure path is not created through the holes. The number of loops of the CFRP strap should be selected such that a flexural failure is achieved if at all possible, which can be done cost-effectively given the flexible nature of the CFRP strap system. If these requirements are followed, a shear enhancement and ductile flexural failure may be possible in beams that have a deficient level of shear capacity. In terms of the development of design models, it has been shown that the designer should carefully consider the load sharing between the concrete, the CFRP straps and the steel shear links in order to ensure the strains in the straps and their contribution are estimated correctly. In particular, an approach that takes in to account the crack widths would seem to be appropriate for further model development.

Conclusions

The goals of this research program were to develop a technique for installing a CFRP strap retrofitting system without requiring access to the top surface of the beam but which would result in significant strength enhancement. It was found that the CFRP straps must encompass a sufficient depth of the compression flange in order to be effective as otherwise shear cracks develop above the CFRP straps and the straps provided minimal shear enhancement. The concrete strength and CFRP strap spacing affect the level of strain in the straps which has a corresponding effect on the load sharing between materials. This has implications for the design of retrofitting systems using these CFRP straps since an accurate prediction of the strap strain will be required to predict the specimen capacity. When compared with the unretrofitted specimen, the specimens with the CFRP straps were found to have a stiffer response once shear cracks had developed. This is because the straps act as additional transverse reinforcing, reducing the amount of load taken by the steel stirrups. Loading pads that were not the full width of the specimen caused premature failures and unfilled holes in the compression flange seemed to serve as shear crack inducers and should also be avoided. Once these problems were overcome, it was found that a CFRP strap under-slab installation technique involving grouted holes provided full shear enhancement to the beams. This research has shown that the CFRP strap strengthening system can be installed effectively without requiring access to the slab surface and still provide significant shear capacity enhancement.

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Table 1 – Steel reinforcement properties

Bar Diameter (mm)	Yield Strength (MPa)	Yield Strain	Elastic Modulus (GPa)	Ultimate Strength (MPa)
6	578*	0.00501*	187.4	646
8	467	0.00233	200	540
16	505	0.00262	192.9	586
20	523	0.00263	198.7	633

* using the 0.2% offset method

Table 2 – Specimen capacities

Specimen	f_{cu}, (MPa)	Ultimate Shear Force (kN)	Percentage Increase versus B1/25	Maximum Mid-span Deflection (mm)	Failure Mode
B1/25	24.8	88.2	-	15.5	Shear in Concrete
B2/45/H/20	19.8	95.4	8.2	15.6	Shear in Concrete
B3/30/H/22	22.3	91.4	3.6	16.0	Shear in Concrete
B4/30/G/25	24.6	105.2	19.3	16.9	Shear in Concrete
B5/30/C/27	26.7	111.0	25.6	16.9	Shear in Concrete
B6/30/C/44	44.0	140.9	59.8	22.1	Shear in Concrete
B7/30/G/36	36.1	134.7	52.7	29.1	Flexure
C1/50	50.0	100.0	13.4	NA	Shear in Concrete
C2/45	45.0	148.0	67.8	NA	Flexure

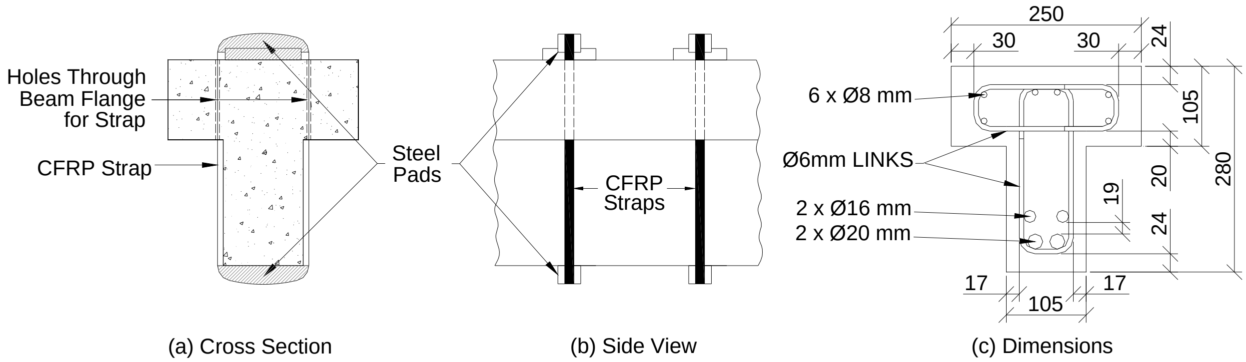


Fig. 1 – CFRP strap layout and cross-section dimensions

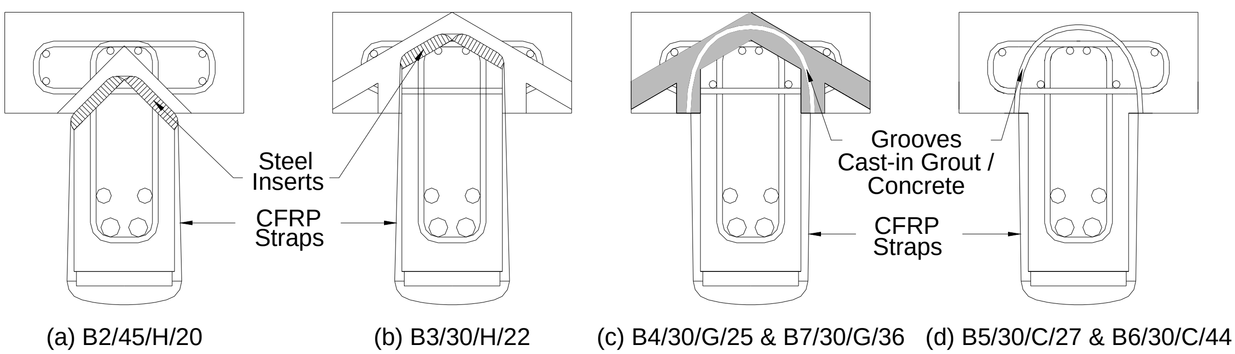


Fig. 2 – Strap configurations for test specimens

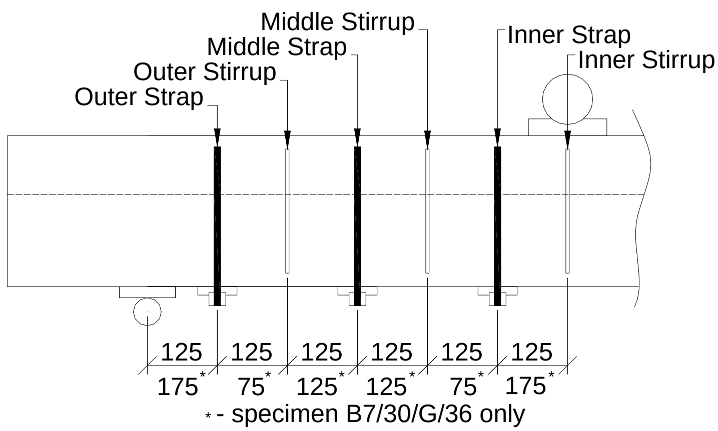


Fig. 3 – Strap and stirrup locations

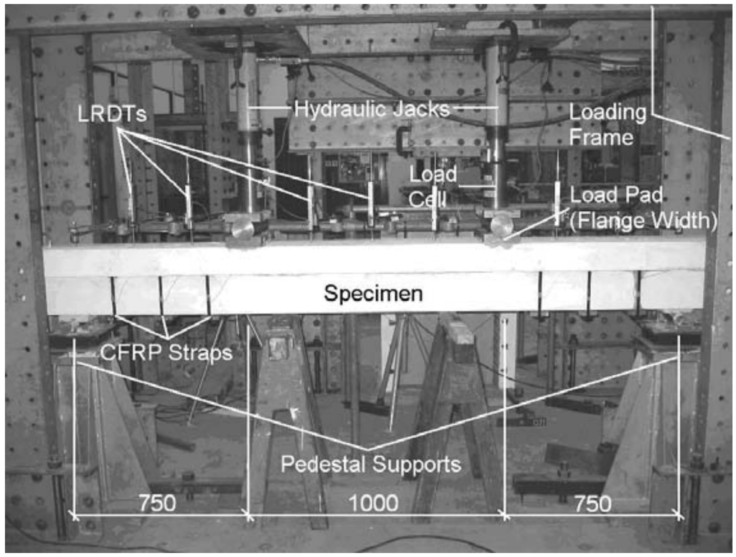


Fig. 4 – Testing rig

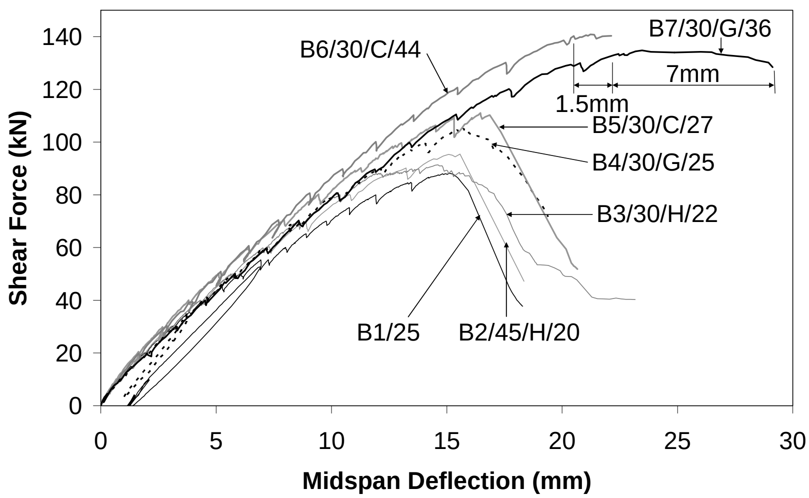
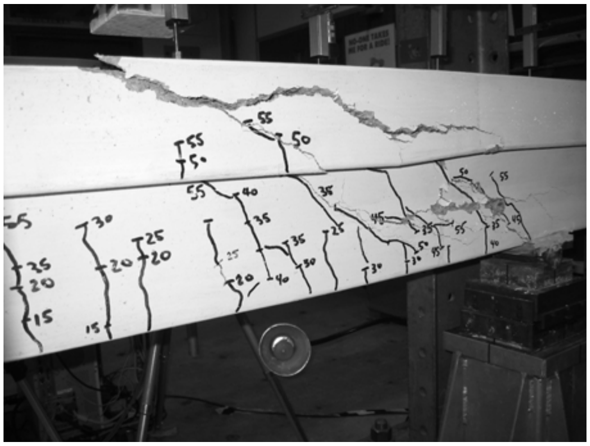
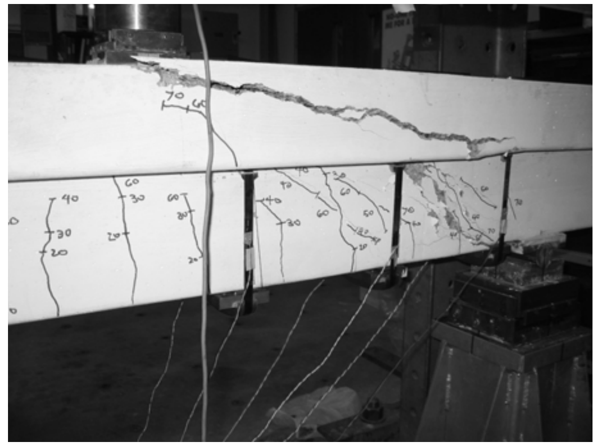


Fig. 5 – Shear force vs. mid-span deflection





a) B1/25 **b) B2/45/H/22**

Fig. 6 – Failure of specimen B1/25 versus B2/45/H/22

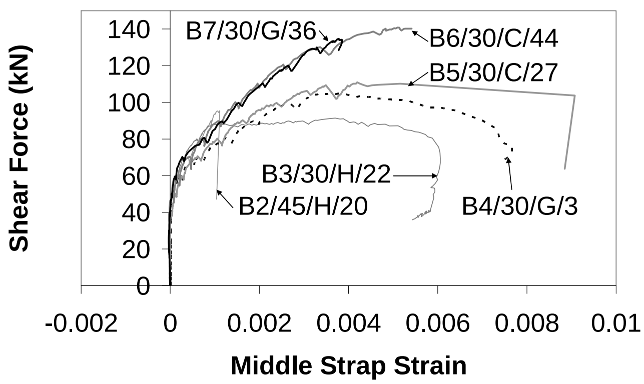


Fig. 7 – Shear force vs. middle strap strains

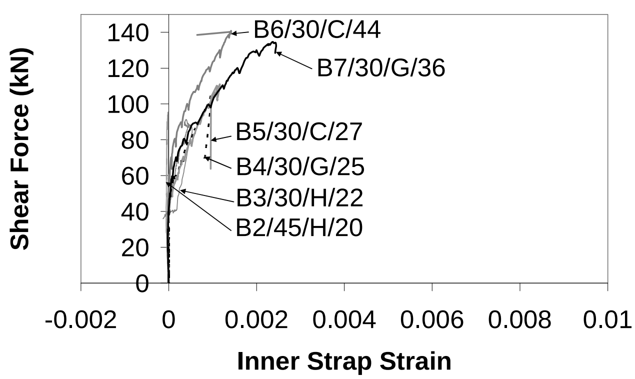
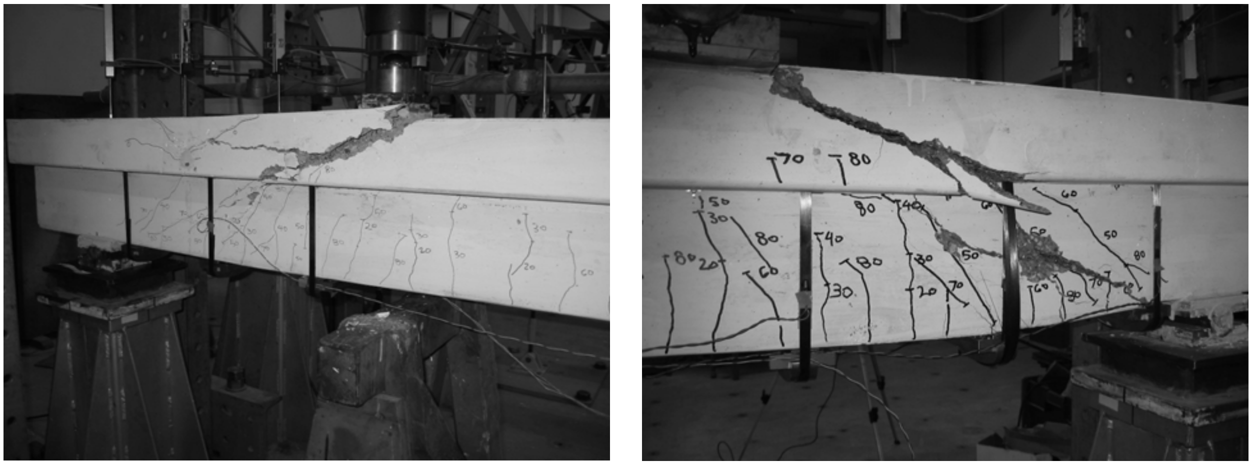


Fig. 8 – Shear force vs. inner strap strains



a) B4/30/G/25 **b) B6/30/C/44**

Fig. 9 – Failure of specimen B4/30/G/25 versus B6/30/C/44