Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)
22-24July 2008, Zurich, Switzerland

Flexural behavior of concrete beams strengthened with steel reinforced polymers

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ABSTRACT: The successful application of composites for structural upgrade has motivated the development of other novel low-cost reinforcement systems that exhibit excellent structural properties. The ability to put very high tensile strength steel into a fabric that can be incorporated into composites was one of the particular interests to the engineering communities worldwide. This paper examines the feasibility and potential of using high-strength steel reinforced polymers (SRP) to strengthen reinforced concrete beams. A total of seven concrete beams (150x300x3000 mm) were constructed and tested under four point bending to evaluate the effectiveness of the strengthening scheme. The influence of the type of the bonding agent, number of plies and the arrangement of the U-wraps along the length of the concrete beams is investigated. Test results showed that SRP could improve both the flexural stiffness and the ultimate load carrying capacity considerably. The flexural capacity was increased by more than 300% using multiple plies of SRP sheets. For the majority of the tested beams, failure was dominated by delamination of the sheets from the concrete surface. Using U-wraps along the length of the beam prevented this type of failure and allowed full utilization of the tensile strength of the sheets.

1 INTRODUCTION

Various rehabilitation techniques have been proposed for civil infrastructure to overcome problems associated with the aging process, change in use, and deterioration. Among these techniques, external strengthening, which provides a practical and cost effective solution when compared to other traditional repair methods (Hassan & Rizkalla 2002). The first generation of external strengthening methods utilized steel plates bonded to the tension surface of the structure. The strengthening effectiveness was acceptable. However several problems, including durability, heavy weight, handling, and shoring had to be resolved and thus the need for alternative materials has aroused. The introduction of advanced composite materials, particularly fiber reinforced polymers (FRPs), in structural engineering industries, as a second generation of externally bonded retrofit materials, has offered numerous benefits (i.e. corrosion-free, excellent weight-to-strength ratio, good fatigue resistance, flexibility to conform to any shape , and broad applications). In the early nineties of the last century, a real explosion of research and development took place through the use of FRPs for strengthening applications. The most imperative characteristic of FRPs in repair/strengthening applications is the speed and ease of installation. Although the applications of FRPs are becoming wider and popular, the cost of material is still relatively high. Steel reinforced polymers (SRP) consists of high-carbon unidirectional steel hardwire fabrics embedded in polymer matrix. SRP is a new family of composite materials based on unidirectional high carbon steel cords with a micro-fine brass or AO-brass (adhesion optimized) coating. Each cord is made by twisting steel wires embedded into a polymeric resin. SRP is a less expensive composite that is currently considered for numerous applications in civil engineering including bridges (Kim et al., 2005; Wobbe et al., 2004). Performance of a composite material utilizing steel wires is controlled by the stress transfer between the wires and the matrix. A single high-strength wire may be deficient due to its low interfacial shear strength and stiffness. This problem is solved in SRP by using twisted steel filaments forming the cord where the rough surface of the cord provides a mechanical interlock with the matrix resulting in a system suitable for structural applications. The type and/or the number of cords per unit width may be selected to optimize the performance for each application. In the reinforcement sheet, the steel cords are held together using a scrim or tape backing, as shown in Figures 1 & 2.

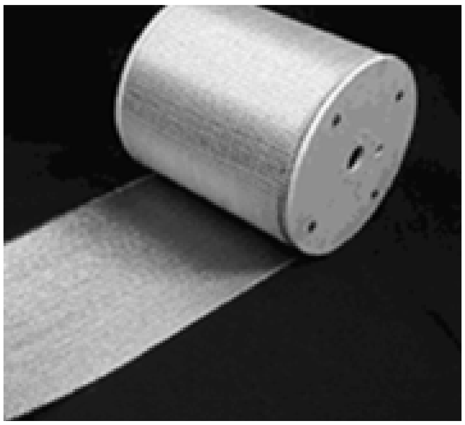

Figure 1. SRP tape

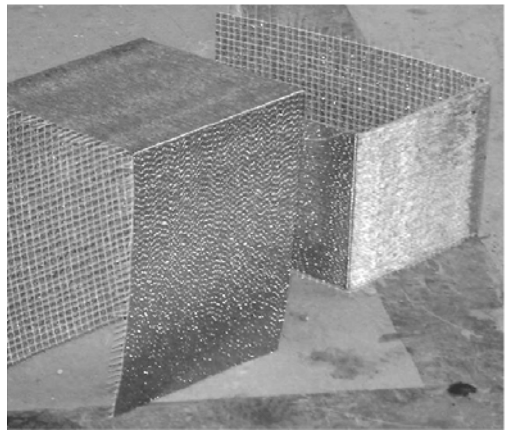

Figure 2. SRP U-Wraps

2 EXPERIMENTAL PROGRAM

Seven simply-supported rectangular reinforced concrete beams of 150 x 300 mm cross sectional dimensions and 3000 mm long were constructed and tested at the Structural Laboratory of Ain Shams University. All beams were reinforced with two 10 mm diameter bars at the top and two 12 mm diameter bars at the bottom. The concrete cover was set to 40 mm on all sides. The beams were adequately reinforced for shear using 10 mm diameter (two-leg) steel stirrups, spaced every 150 mm to prevent shear failure. The test specimens includes one control beam, three beams strengthened using variable plies of SRP sheets, two additional SRP-strengthened beams with U-wraps anchored at both ends of one beam and distributed along the entire length of the other beam. The last beam was strengthened with SRP using a different type of adhesion material to investigate the influence of the adhesion type on the structural performance. Details of the test specimens are shown in Figure 3a. Three Linear Variable Displacement Transducers (LVDTs) were used to monitor the deflection under the applied loads and at the middle span of the beam. Electrical resistance strain gauges were installed at various locations on the SRP sheets to establish the strain distribution along the length of SRP sheet under increased load levels. A hydraulic jack of 400 kN capacity was used to apply the load on the test specimens as shown in Figure 3b.

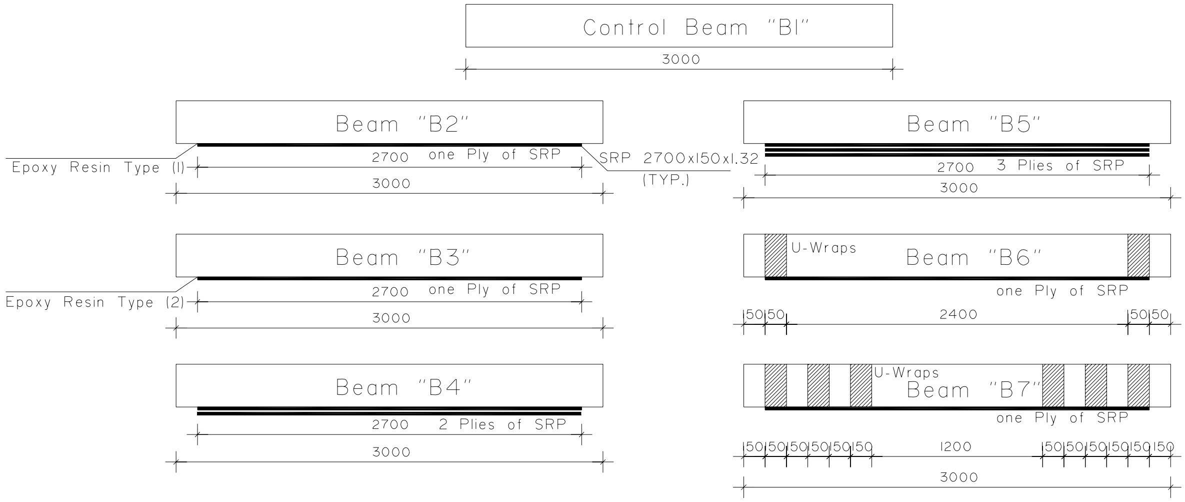

Figure 3a. Details of the test specimens

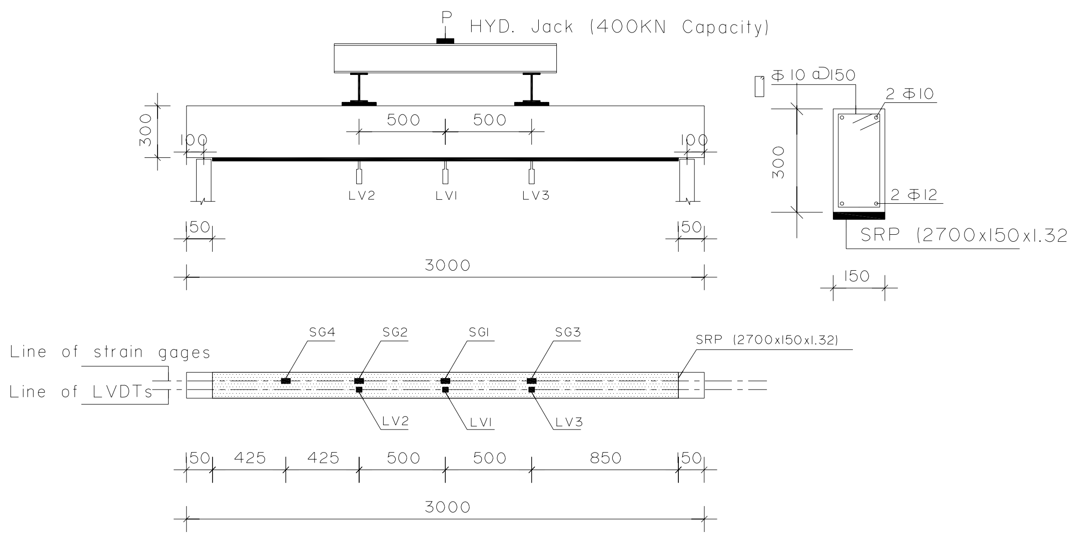

Figure 3b. Test setup

3 MATERIALS

3.1 *Concrete and steel reinforcement*

Six standard concrete cubes (158x158x158 mm) were cast along with the concrete beams and were tested to determine the concrete compressive strength. The average concrete cube compressive strengths at 28 days and at the day of testing were 36 MPa and 39 MPa, respectively. The steel reinforcement used in the current study has a yield strength and elastic modulus of 360 MPa and 200 GPa, respectively.

3.2 *Epoxy resin*

Both types of epoxy resins used in the current study consist of components A and B, which are mixed at a ratio of 4:1 by weight and stirred until a homogenous mixture is obtained. Both types have almost identical tensile and flexural strength. However, the bond strength was relatively different. According to the manufacturer, the bond strength of Type 1 resin was 34 MPa, which is 23 percent less than that of Type 2.

3.3 *Steel reinforced polymers (SRP)*

The SRP hardwire materials used in the current study consist of twisted high-carbon steel cords (3SX-21-12 Hardwire) embedded into a polymeric resin. Each steel cord is made by twisting three identical wire filaments together and then over-wrapping the bundle with a single filament. Each steel cord has a nominal diameter of 1.016 mm. The composite laminate thickness is 1.32 mm. The laminate has a linear tensile stress-strain behavior with a tensile strength of 840 MPa and an elastic modulus of 75 GPa.

4 SPECIMEN PREPARATION

In order to guarantee an adequate bond between the concrete surface and the SRP, the tension face of all beams was sandblasted until coarse aggregates were exposed and all laitance, dust and dirt were removed using air pressure, as shown in Figure 4.

Figure 4. Surface preparation of the test specimens

Prior to application of the SRP sheets, the epoxy was mixed per manufacturer specifications and was rolled onto the roughened face of the beam. Unidirectional hardwire fabrics were then applied and pressed into the epoxy with a rib roller. Additional layer of epoxy was applied to completely cover the cords. The same procedures were applied for specimens strengthened with multiple plies of SRP sheets. Typical application procedures of the SRP sheet are illustrated in Figure 5.

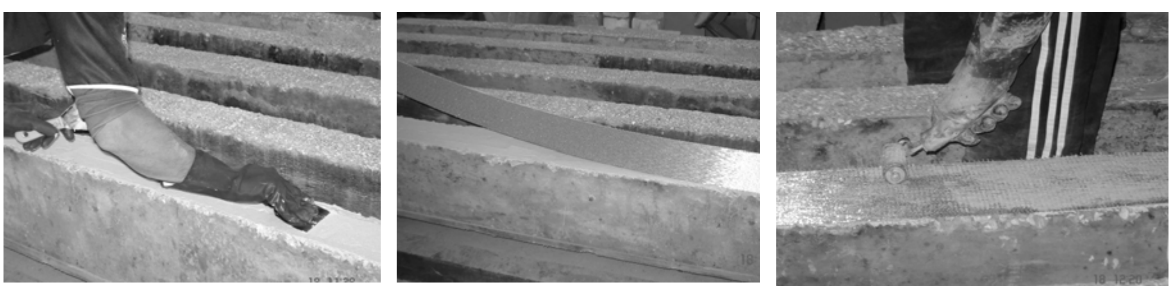

Figure 5. Typical application procedures of SRP

5 RESULTS AND DISCUSSION

The load-deflection behavior at mid span of each specimen is shown in Figure 6. Linear behavior was observed up to initiation of the first flexural crack at a load level around 25 kN followed by a non-linear behavior up to failure. Failure of the control specimen was due to crushing of the concrete in compression after yielding of the bottom steel reinforcement at a load level of 43 kN. In general, using externally bonded SRP sheets enhanced both the post-cracking stiffness and ultimate load carrying capacity considerably. The load-tensile strain behavior of the strengthened specimens is shown in Figure 7. It should be noted that no significant difference was observed between specimens B2 and B3 strengthened with one ply of SRP sheets and bonded using two different adhesives. Both specimens behaved similarly with the same pre- and post-cracking stiffness up to failure. Failure of these specimens was dominated by delamination of the SRP sheets. The difference in failure loads of the specimens was less than 10 percent. The corresponding tensile strain in the sheets at the onset of delamination was in the range of 0.6-0.75 percent, which is around 50 percent of the ultimate strain of the sheets. Increasing the number of SRP plies significantly increased the post-cracking stiffness as well as the ultimate load carrying capacity as was observed in specimens B2, B4 and B5 strengthened using one, two and three plies of externally bonded SRP sheets, respectively. Failure of specimen B2 strengthened with one ply of SRP sheets took place at a load level of 118 kN, which is almost three times the capacity of the control specimen. Using two and three plies of SRP sheets (specimens B4 and B5) increased the ultimate load carrying capacity by an additional 25 and 50 percent, respectively. It should be noted that the strain level associated with delamination of the SRP sheets decreased by increasing the number of plies as clearly demonstrated in Figure 7. This behavior could be attributed to the increased thickness of the SRP material. Therefore, the shear strength at the interface is reduced leading to premature delamination of the sheets from the concrete. Test results showed that using U-wraps at the beam ends only did not provide any additional strength or enhanced the behavior of the strengthened beam. Specimen B6 strengthened with only one ply of SRP sheets with U-wraps at the ends exhibited the same behavior, failure mode and ultimate load carrying capacity as those observed for specimens B2 and B3. Delamination of the sheets started at the vicinity of the U-wraps and propagated rapidly towards mid-span. Conversely, using six U-wraps equally spaced along the entire length of the beam allowed full utilization of the strength of the sheets and precluded premature delamination of the sheets. Failure of specimen B7 (with U-wraps distributed along its entire length) was primarily controlled by rupture of the sheets at a load level of 147 kN, which is 3.5 times that of the control specimen. The corresponding strain at failure was 1.3 percent.

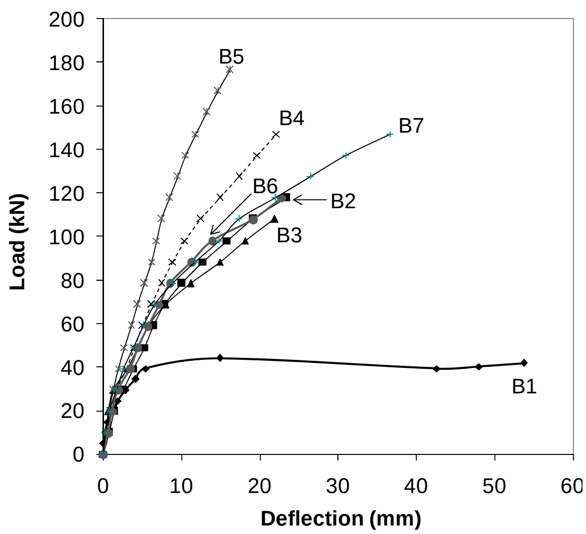

Figure 6. Load-mid span deflection behavior

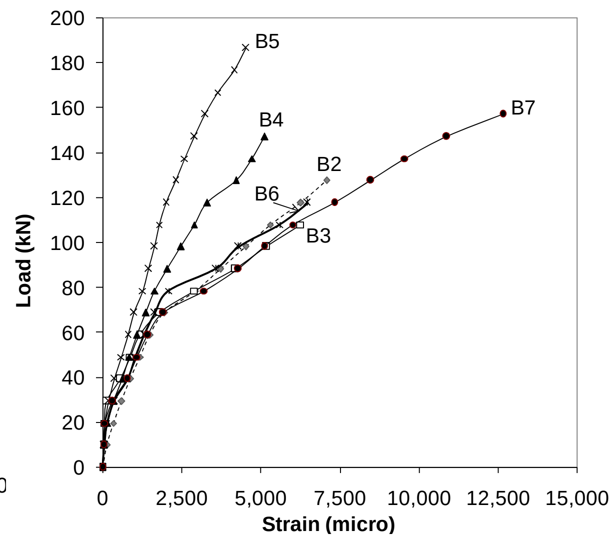

Figure 7. Load-tensile strain behavior

Different failure modes of the strengthened specimens are shown in Figure 8. Delamination failure was observed for all the specimens except that strengthened with U-wraps along the entire length of the beam (specimen B7). For specimens B2, B3, B4 and B5, horizontal cracks developed due to the stress concentrations at the cut-off point of the SRP sheets, and propagated along the level of the internal reinforcement, towards mid-span. However, for specimen B6, which was strengthened with U-wraps at the beam ends, delamination occurred as a result of flexural cracks at mid-span. Using U-wraps along the entire beam length (specimen B7) provided additional restraints to propagation of delamination-type cracks and allowed full utilization of the tensile strength of the sheets.

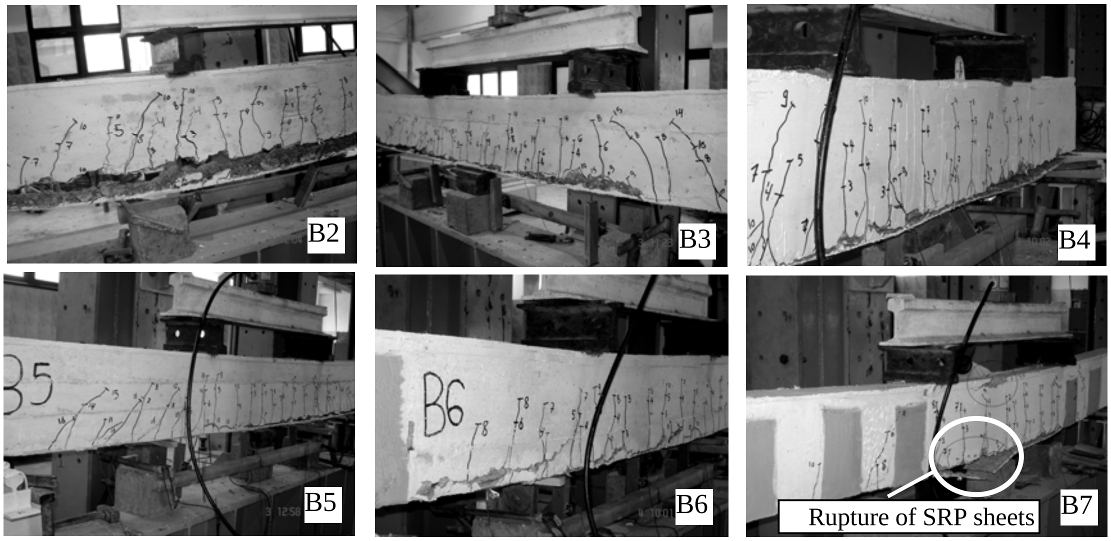

Figure 8. Failure modes of different specimens

6 CONCLUSIONS

Based on the findings of the current study, the following conclusions could be drawn:

1- Using externally bonded SRP sheets enhanced both the post-cracking stiffness and ultimate load carrying capacity considerably. Using one ply of SRP sheets increased the ultimate load carrying capacity by 300 percent compared to the control specimen. Test results showed that using two and three plies of SRP sheets increased the ultimate load carrying capacity by an additional 25 and 50 percent, respectively.
2- No significant difference was observed in behavior, crack pattern or mode of failure of specimens strengthened using SRP sheets bonded using different adhesives. The observed failure loads were within 10 percent.
3- Using U-wraps at the beam ends only did not provide any significant enhancement in strength and did not alter the observed mode of failure due to delamination of the sheets. Conversely, using equally-spaced U-wraps along the entire length of the beam, allowed full utilization of the strength of the sheets and precluded delamination of the sheets. The confining effect of U-wraps reduced the slip of longitudinal SRP sheets that resulted from shear deformation of the resin at the interface between the concrete and SRP sheet.

7 REFERENCES

Hassan T. and Rizkalla, S. (2002) “Flexural Strengthening of Post-Tensioned Bridge Slabs with FRP Systems”, PCI Journal, Vol. 47, No. 1, pp.76-93.

Kim, Y. J., Fam, A., Kong, A.,.Green,M., 2005, “Flexural Strengthening of RC Beams using Steel Reinforced Polymer (SRP) Composites, http://www.hardwirellc.com/Downloads/Queens_Flex_Strengthening_RC_Beams.pdf.

Wobbe, E., Silva, P., Barton, B., Dharani, L., Birman, V., Nanni, A., Alkhrdaji, T., Thomas, J., and Tunis, G., 2004,”Flexural Capacity of RC Beams Externally Bonded With SRP and SRG, http://www.hardwirellc.com/Downloads/Flex_Capacity.pdf.