Prestressing system for FRP strengthening steel-concrete composite girders

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ABSTRACT: Recently, the use of Fiber Reinforced Polymers (FRP) composites for strengthening steel structures has received great attention. By prestressing the externally bonded (EB) FRP laminates, the material is used more efficiently as a greater portion of its tensile capacity is employed and it contributes to the load bearing capacity under both service and ultimate conditions. An innovative mechanical anchorage system was developed to prestress the FRP laminate against the girder itself. The new system depends on bonding the strengthening material using epoxy adhesive to steel anchors that will be attached to the steel beam with bolts and prestressed to the required force. The developed anchorage/prestressing system was practical and easy to use and succeeded to prestress the FRP laminate up to 50% of the material ultimate capacity.

1 INTRODUCTION

Metallic bridges may become structurally deficient for wide variety of reasons. Several researchers investigated the behaviour of the steel beams strengthened with non-prestressed FRP such as Sen et al. 1994, Karbhari & Shulley 1995 and Miller et al. 2001. Recently, Ragab & El-Hacha (2007) tested steel-concrete composite girders strengthened using intermediate modulus Carbon FRP plate, and Steel Reinforced Polymer (SRP) sheets. The increase in the yield and ultimate loads for the strengthened beams with respect to the unstrengthened control beam were 22.5 %, 29.0 %, 31.0 % and 37.4 %for the CFRP plate and SRP sheets, respectively. The authors also concluded that the SRP sheets were much more cost efficient than the CFRP. Although strengthening using EB FRP enhanced the flexural resistance of the beam, it doesn’t affect the serviceability behaviour of the member. Therefore, the need to enhance the serviceability behaviour of the member with the increase of flexural resistance is required. By prestressing the EB FRP, the material is used more efficiently as a greater portion of its tensile capacity is employed and it contributes to the load carrying capacity under both service and ultimate conditions. Few researchers investigated the behaviour of beams strengthened with prestressed FRP such as Colombi et al. (2003) and Schnerch et al. (2005) who investigated the serviceability behaviour of steel-concrete composite beams strengthened with prestressed high modulus CFRP strip. The process of prestressing was conducted by bonding the CFRP strips to a special steel tab. The adhesive was applied to the CFRP strips and additional adhesive was applied to the steel surface facing the CFRP strips and the jacking force was applied by tightening threaded rods. The force was monitored by strain gauge placed on the CFRP strips at mid-span. After reaching the required strain, the CFRP strips were bonded to the steel beam using the same procedure used with the non-prestressed CFRP strips. The authors concluded that prestressing CFRP strips is an economical use of material and increases the stiffness of the beam under a service load by 31 % while maintaining the original ductility of the section. The main objective of the study presented in this paper is to develop an innovative practical mechanical anchorage/ prestressing system for prestressing the CFRP plate and the newly developed SRP sheets against the beam itself.
2 EXPERIMENTAL PROGRAM

2.1 Material Properties

2.1.1 Steel Reinforced Polymer (SRP) Sheets

A unidirectional ultra-high strength Steel Reinforced Polymer (SRP) sheet type 3×2-23 manufactured by HardwireTM was used. The SRP sheet is made of high carbon steel cords with microfine brass or AO-brass (Adhesion Optimizer) coating. The sheet consists of 23 steel cords per inch. Each cord is composed of three straight filaments warped with two filaments at a high twist angle. The area used in this experiment was 201.72 mm² and was formed using two layers of SRP sheets with 82 mm wide each. The sheets were bonded to steel anchors using Sikadure®330 epoxy resin. According to the manufacturer, the tensile strength and modulus of elasticity of the SRP sheet are 1133 MPa and 75600 MPa, respectively.

2.1.2 Intermediate Modulus Carbon Fiber Reinforced Polymer (CFRP) Plates

A pultruded Intermediate Modulus Carbon Fiber Reinforced Polymer (CFRP) plates was used. The CFRP plate is bonded to steel anchors using Sikadure®330 epoxy adhesive. The beams were strengthened using one layer of CFRP plate with a total area of 96 mm². The tensile strength and tensile modulus of elasticity, as provided by the manufacturer, are 2800 MPa and 165000 MPa, respectively.

3 DEVELOPMENT OF THE PRESTRESSING ANCHORAGE SYSTEM

A practical mechanical anchorage system was developed to prestress the FRP material against the girder itself. The new system depends on bonding the strengthening material using epoxy adhesive to steel anchors that will be attached to the steel beam with bolts and prestressed to the required force. The beam to be strengthened is prepared to allow the attachment of the anchorage/prestressing system by drilling eight 21 mm diameter holes in the beam bottom flange (four on each side).

The anchorage/prestressing system consists of nine parts. The strengthening material is attached to two main parts, a fixed anchor to be used at the dead end and a movable anchor to be used at the jacking end. The other seven parts to be used at the jacking end include fixed angle, threaded rod, steel chair, hydraulic jack, load cell, lock nut, and a loose nut.

3.1.1 The Fixed Steel Angle

A steel angle (L152 × 152 × 12) is fixed to the bottom flange of the steel beam using four 19 mm diameter bolts as shown in Figure 1. Four stiffeners are welded to prevent the vertical leg from bending under the prestressing force. The vertical leg of the angle is cut to fit the beam’s bottom flange. Two HSS steel sections are welded to the bottom of the steel angle, so as to carry the movable anchor before the prestressing force is applied, as well as to resist any possible rotation of the movable anchor due to the eccentricity between the applying force level and the FRP material. Two 21 mm diameter holes are drilled in the vertical leg of the angle to allow the threaded rod to connect the movable part to the fixed angle.

3.1.2 The Fixed Steel Anchor

The fixed anchor consists of a steel plate (Pl 330 × 102 × 10 mm) which has four 21 mm holes to allow for a four 19 mm diameter bolt connection to the steel bottom flange as shown in Figure 1. As the beam would camber due to the prestressing force, the tensioned FRP may bend the steel plate to remain straight. For this reason, three steel stiffeners (330 × 20 × 5 mm) are welded to the steel plate to prevent any possible bending. A small tapered piece of steel plate (Pl 102 × 40 × 10 mm) is welded to the end of the steel plate to make sloped end. This sloped end allows the placement of the additional CFRP sheets on other side of the steel plate without having a sharp angle in the transition zone between the FRP and the steel plate. This also increases the bond area between the strengthening material and the steel plate.
3.1.3 *The Movable Steel Anchor*

The movable anchor consists of a steel angle (L102 × 152 × 12). The vertical leg is cut to allow
the angle to be attached to the steel beam bottom flange as shown in Figure 2. The steel angle is
stiffened with four stiffeners to prevent the angle vertical leg from bending under the applied
tension force. Similar to the fixed steel anchor and for the same reasons, a small tapered piece of
steel (Pl 102×100×10 mm) is welded to the angle. Two 21 mm holes are drilled in the vertical
leg of the angle to allow the threaded steel rod to pass through the angle.

![Figure 1. Schematic drawing of the steel fixed anchor and fixed steel angle](image)

![Figure 2. Schematic drawing of the steel fixed anchor](image)

3.1.4 *Other Prestressing System Parts*

![Figure 3. Schematic drawing for anchorage/prestressing system](image)
Two 19 mm diameter threaded steel rods are used to transfer the tension force from the jacks to the moveable steel anchor (Fig. 3). On each side of the beam, one jack was used to apply the tension force and a load cell was used to measure the prestressing force. Steel chair is positioned to allow the removal of the hydraulic jack and the load cell after reaching the target prestressing force. Two nuts are placed before the fixed angle and after the load cell to lock the system before prestressing and permit the movable part to move in one direction only. Two loose nut is located inside the steel chair on the steel threaded rod. This nut locks the movable anchor allowing the removal of the load cell and the jack after reaching the target prestressing force.

4 BEAM STRENGTHENING PROCEDURE

4.1.1 Bonding the Strengthening Material to the Anchors

The epoxy adhesive was applied to the steel anchors using a special putty knife to guarantee that the thickness of the adhesive was as recommended by the manufacturer. The strengthening material was flipped onto the adhesive on the steel anchors and a slight pressure was applied to ensure uniform distribution of the epoxy under the FRP. In order to enhance the bond between the strengthening material and the steel anchor, four additional layers of CFRP sheets with length of 500 mm and width of 80 mm were placed at the end to cover the strengthening material as shown in Figure 4. The CFRP sheets doubled the bond area, which increased the capacity of the anchors/FRP to resist the occurrence of slippage at high loads. Finally, a small piece of wood covered with a plastic sheet was placed on top of the bonded area of FRP material to ensure sustained pressure on the epoxy until it cured. In case of using multiple layers of FRP material, a uniform 1 mm thickness of epoxy is applied between the layers to ensure a perfect bond.

Figure 4. CFRP sheets glued to the SRP sheets at both the fixed and movable anchors

4.1.2 Second Stage: Prestressing and Bonding to Steel Beam

The fixed end anchor was attached to the beams using four 19 mm diameter bolts. The movable end anchor was placed on the HSS legs welded to the fixed steel angle. The threaded rods were inserted through the holes in both the movable anchor and the fixed angle. On each side of the strengthening system, the loose nut was attached to the threaded rod followed by the steel chair, the hydraulic jack, and the load cell. The lock nut was then placed before the fixed angle and after the load cell to lock the entire system. Securing the fixed angle with the lock nuts prevented movement of the movable anchor towards the direction of the beam. By pumping oil to the hydraulic jack, the plunger cylinders began to move forward. This caused the movable anchor to move forward in the direction of the fixed angle and generates tension force in the FRP material. The force was transferred from the jack to the threaded rod and to the movable anchor. The induced prestress force was measured by the load cell and the strain gauges attached along the length of the FRP material at different locations. The constraint move of the movable anchor makes the steel chair move away from the loose nut. After reaching the required prestressing force, the loose nut was rotated by hand until it locked the movable anchor. After locking the loose nut, the pressurized oil was released from the hydraulic jack and resulted in a transfer of all the forces to the FRP material. This allowed the removal of the lock nut behind the load cell, the load cell and the hydraulic jack.
5 ANCHOR TEST

Several tests were undertaken to determine the efficiency of the developed anchorage system in tensioning the FRP material. The specimen was prestressed to failure which was dominated by debonding between the FRP and the steel anchor’s parts. Figure 5 shows the prestressing load versus the strain in the FRP obtained form the anchor test. The Figure shows that the actual strain in the FRP measured from strain gauges didn’t follow the same behaviour as the uniaxial tension test especially at higher loads. This was due to the friction between the movable steel anchor and the fixed steel angle during prestressing.

![Graph showing prestressing load versus strain](image)

**Figure 5. Load versus strain for SRP sheets from tension test and anchor test**

6 EXPERIMENTAL TEST

The experimental test was conducted to investigate the behaviour of six 6000 mm long steel-concrete composite beams strengthened with prestressed externally bonded (EB) SRP sheets and CFRP plate. The FRP was prestressed using the developed anchorage system with three different force levels 16 %, 28 % and 42 % of the ultimate load capacity of the SRP sheets (equivalent to 31, 62 and 97 kN prestressing force) and 11 %, 15 % and 21 % of the ultimate load capacity of the CFRP plate (equivalent to 33, 41, and 61 kN prestressing force). The proposed prestressing/anchorage system succeeded to prestress the beams to the required prestressing force. Figure 6 shows a typical strain profile along the length of the prestressed SRP sheets.

![Graph showing strain profile](image)

**Figure 6. Strain profile in the SRP sheet along beam prestressed with 42 % (97 kN)**

It was observed that the prestress losses that occurred after release and transfer of the prestressing force from the jack to the permanent anchor were negligible compared to the initial prestressing strain. For the beams strengthened with prestressed SRP sheets or CFRP plate, the losses were in the range of 0 to 1.5% and 1.0 to 1.9%, respectively. Figure 7 shows the strain versus time for the beam prestressed with SRP sheets.
CONCLUSIONS

The following conclusions can be drawn from the experimental study conducted on the developed prestressing system:

1. The developed anchorage/prestressing system was practical and easy to use for strengthening both CFRP plate and SRP sheets against the steel-concrete composite girders.
2. The prestressing system succeeded to prestress the FRP material to the required force up to 50% the ultimate strength of the FRP.
3. The prestressing losses after transfer of the force from the jack to the permanent anchors were up to 1.5% and 1.9% for the beams strengthened with prestressed SRP sheets and CFRP plate, respectively.

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REFERENCES