Anchorage of Surface Mounted FRP Reinforcement

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Abstract
This paper presents a novel anchor system called U-anchor that can be used to significantly improve the performance of surface mounted reinforcement for concrete/masonry made of fiber reinforced polymer (FRP) composites. In applications where bond and/or development length of FRP are critical, the U-anchor prevents debonding of the reinforcement. The anchor is based on the idea of embedding a bent portion of the end (or near the end) of the FRP reinforcement into a preformed groove in the concrete/masonry. The groove is filled with a viscous paste and may or may not include an FRP bar. The U-anchor is compatible with any external FRP strengthening system and avoids high stress concentration and durability concerns. It can be used with sheets and pre-cured laminates that are unbonded or fully bonded to concrete. Laboratory testing confirms the excellent performance of the U-anchor system.

Keywords: Bond; End anchor; Externally bonded reinforcement; Fiber reinforced polymer (FRP); Flexural strength; Reinforced Concrete; Repair; Shear strength; Strengthening

1. Introduction

To resolve corrosion problems in reinforcing steel and to increase the efficiency of repair work for the deteriorating reinforced concrete (RC) infrastructure, professionals have turned to alternative materials such as fiber reinforced polymer (FRP) composites (ACI 440 1996). The interest in the use of composites is attributable to declining manufacturing costs combined with ease and speed of installation. FRP composites are made of high strength fibers embedded in a polymer resin (ACI 440 1996). The fibers in these composites are the main load-carrying element and, besides being corrosion resistant, have a wide range of strength and stiffness with a linear stress-strain relationship up to failure. The fiber types that are typically used in the fabrication of FRP composites for construction are carbon, glass, and aramid. The resin surrounds and encapsulates the fibers to bind them together, to protect them from damage, to maintain their alignment, and to allow distribution of load among them. The most common types of polymeric resin are polyester, vinyl ester, and epoxy.

FRP composites can be produced by different manufacturing methods in many shapes and forms; the most popular ones for concrete reinforcement are rebars, prestressing tendons, pre-cured laminates/shells, and fiber sheets. FRP rebars and tendons are currently produced with sizes and deformation patterns reminding of those of steel rebars, strands and solid wires. They are commonly used for internal concrete reinforcement. FRP pre-cured laminates/shells and sheets are commonly used for external concrete reinforcement. FRP plane laminates have been used to replace bonded steel plates

(Sharif and Baluch 1996, Castro et al 1996) and FRP shells have been used as jackets for columns (Xiao and Ma 1997). Dry or pre-impregnated sheets are generally installed by manual wet lay-up after smoothing and preparing the concrete surface. In manual wet lay-up, a fiber sheet is cut to dimension and sandwiched between two layers of impregnating resin resulting into the composite. FRP sheets may be adhered to the tension side of structural members (e.g., slabs or beams) to provide additional flexural strength (Arduini and Nanni 1996). They may be adhered to web sides of joists and beams or wrapping around columns to provide additional shear strength (Chajes et al. 1995, Taerwe et al. 1997, Arduini et al. 1997, Triantaffilou 1998). They may be wrapped around columns to increase concrete confinement and thus strength and ductility of columns (Nanni et al. 1993, Seible and Innamorato 1995). Among many other applications, FRP sheets may be used to strengthen concrete and masonry walls to better resist lateral loads (Hartley et al. 1996, Triantaffilou 1996) as well as circular structures (e.g., tanks and pipelines) to resist internal pressure and reduce corrosion (Arizona Public Service Co. 1997). As of today, several millions square feet of surface bonded FRP sheets have been used in many strengthening projects in the U.S. and all over the world (Nanni 1997). In North America, design guidelines have been or are currently being developed by organizations such as the International Conference of Building Officials (ICBO) and ACI.

2. Anchorage of Externally-Bonded FRP Systems

Although the use of externally bonded FRP composites has been implemented in many strengthening projects, there has always been a concern for the end anchorage. This is particularly important when the length of the FRP system is restricted and the bonded length beyond a critical section is not sufficient to achieve the ultimate strength of the FRP reinforcement. When FRP reinforcement is used for shear strengthening of rectangular or T-section RC beams, the FRP is applied to the sides of the section in the form of a U-wrap or strips with fibers perpendicular to the longitudinal axis of the beam. Shear cracks develop at approximately 45° with respect to the longitudinal axis of the member. As a result, the FRP reinforcement may have minimal bonded length near the flanges of a T-section, usually leading to a premature failure due to debonding. This situation is even more critical in negative moment regions as cracks develop from the topside of the member. Premature failure could be prevented if sufficient end anchorage is provided.

It has been shown that the anchorage of the ends of the sheets with steel plates and bolts is effective and can increase the shear capacity of RC members (Sato et al. 1997). In the case of U-wraps, it was observed that anchoring increased the shear capacity by about 20% above that of specimens with no end anchorage (Sato al. 1997a). Mechanical anchors made of steel, although effective in the laboratory, are not very practical for field application due to drawbacks such as stress concentration and, in the case of bolting, discontinuity of the FRP at drilling locations. In the case of carbon FRP, the likelihood of galvanic corrosion due to steel-carbon fiber contact is also a concern.

3. New Anchor System

In order to address the problems associated with traditional anchors, an innovative anchoring system was developed at the University of Missouri-Rolla using FRP materials only. The system has been called U-anchor. The U-anchor can be used with FRP sheets and pre-cured laminates that are unbonded or fully bonded to concrete or masonry. The idea is to embed a bent portion of the end (or near the end) of the FRP reinforcement into the concrete or masonry. In the case of fiber sheets, the bent is created during wet lay-up and, in the case of laminates, the bent is pre-formed. For simplicity, reference from here on is only made to the case of fiber sheets.

The sketches of Fig. 1 show three possible uses of the U-anchor: away from corner (on a plane surface), after corner, and before corner. Typical applications of the U-anchor system are shown in Fig. 2. The applications include:

- Before and after corner end anchors of U-wraps for shear strengthening of beams (Fig. 2(a) cases ① and ②)
- Before and after corner end anchors of sheets for flexural/shear strengthening of walls and columns (Fig. 2(b) case ②)
- Plane surface anchorage of sheets for flexural strengthening of beams and slabs (Fig.s 2(b) case ① and 2(c))

4. Application Procedure of the U-Anchor

The anchoring of the FRP reinforcement is attained by grooving the concrete near the end of the FRP sheet. The groove is cut perpendicular to fiber direction. Concrete can be grooved using conventional tools and technology. For example, one can make two parallel saw cuts on the concrete surface having predetermined depth and spaced at a distance equal the required width of the groove. The concrete in between the two cuts is then chipped off.   In the case where the groove is before a corner or on a plane surface, the edges of the groove should be rounded off (e.g., for carbon FRP a minimum radius of 10 mm is suggested). This is intended to reduce stress concentration and prevent premature breakage of the FRP composite.

The groove walls may be roughened by sandblasting. The groove is cleaned (e.g., pressured air) to remove all loose particles and dust. The strengthening work of the structural concrete member is then carried out starting with concrete surface preparation and priming that includes the walls of the groove. The FRP reinforcement is bonded to the concrete surface and to the walls of the groove. After the resin impregnating the sheet (saturant) has set (e.g., approximately one hour), the groove is filled half way with a high viscosity binder (e.g., epoxy paste) compatible with the FRP systems. The high viscosity paste ensures easier field execution, especially in the case of over-head application. An FRP bar is then placed into the groove and is lightly pressed in place. This action forces the paste to flow around the sheet and to cover simultaneously part of the bar and the sides of the sheet. The bar can be held in place using wedges at the appropriate spacing (or totally removed). The groove is then filled with the same paste

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and the surface is leveled. A cross section showing details of the final product is shown in Fig. 3. This is an "after corner" type U-anchor.

As a variation of the installation procedure described above, the end of the FRP sheet can be rolled around the bar during the first saturant impregnation and the bar can be wedged tightly into the groove. In this case, the paste is only added as the final step. The system can also be applied with or without an FRP bar and can be used to anchor continuous (inside or outside lap) as well as discontinuous sheets, as shown in Fig. 4.

If the U-anchor is not specifically designed for the intended application, a recommended FRP bar diameter is 10 mm and groove dimensions can be taken as 1.5 times the bar diameter.

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5. Example of Experimental Validation

The following describes an example of experimental validation of the effectiveness of the U-anchor for the case of RC beams strengthened in shear with CFRP wraps.

A. Test Specimens and Materials

Three, full-scale, simply-supported, RC beams were tested using four-point loading. The beams had a T-shaped cross-section and were reinforced with longitudinal steel rebars and no stirrups in the test region. Specimen details and dimensions are shown in Fig. 5. The materials used for manufacturing the test specimens and their mechanical properties are listed in Table 1.

B. Strengthening Schemes and Setup Configurations

Specimen BT1 was the reference beam. Specimen BT2 was strengthened using surface bonded U-wraps throughout the beam span. The wraps were made of single-ply CFRP sheets with the fiber in the direction perpendicular to the longitudinal axis of the beam (90-degree). No end anchors were used for specimen BT2. The CFRP wraps were applied following the manufacturer's recommendations (MBT 1998). Prior to strengthening, the concrete surface was prepared using sand blasting. It was then coated with a layer of epoxy-based primer, which penetrates the concrete pores and provides better bond properties. After the primer became tack-free, a layer of putty, a thick paste epoxy, was applied to level the surface and patch small holes. A first coat of saturant resin was then applied followed by the fiber sheets. A ribbed roller was used on the sheets to ensure impregnation of the fibers by the saturant. The sheet was then coated with a second layer of saturant resin and the excessive resin was removed.

Specimen BT3 was strengthened in a manner similar to that of specimen BT2. The ends of the U-wrap in specimen BT3 were anchored to the flanges on both sides of the beam using the U-anchor system, as shown in Fig. 1b. In this case, deformed Glass FRP rods having a diameter of 10 mm were used to anchor the sheets. Photographs showing the sequence of steps for CFRP sheets and anchor installation are given in Fig. 6. Test setup and strengthening schemes of the tested beams are shown in Fig. 7.

Four linear variable differential transformers (LVDTs) were used for each test to monitor vertical displacements at various locations. Two LVDTs were located at mid span, one on each side of the beam. The other two were located at the beam supports to record support settlement. Strain gauges were attached to the FRP on the sides of beams BT2 and BT3 and oriented in the fiber direction. Ten strain gauges were used for each beam to monitor FRP strain during loading. Strain gauges were mounted at the expected location of shear cracks (as observed in reference beam BT1 during testing). Strain gauges positions are shown in Figs. 7(b) and 7(c).

C. Test Results and Discussion

When beam BT1 was loaded, it exhibited diagonal shear cracks at a load of 110 KN. The shear cracks started at the center of both shear spans simultaneously. The first shear

crack was the critical crack in the beam. As the load increased, this crack started to widen and propagated leading to the eventual failure at a load of about 180 KN.

In beam BT2, failure was initiated by debonding of CFRP sheets over the main shear crack in the same location observed in beam BT1. It was followed by shear compression failure at a load of 310 KN. Strengthening of beam BT2 with FRP U-wraps resulted in a 72% increase in the shear capacity. The maximum localized FRP strain was in the order of 0.0045 mm/mm, which corresponds to 28% the reported ultimate strain of the CFRP. If delamination could be prevented, a better utilization of the strengthening material and consequently a higher increase in shear capacity of the beam would be attained.

As a result of the use of U-anchors, a significant increase in the shear capacity was achieved in beam BT3. Also, the failure mode changed from shear compression (as observed in beam BT2) to flexural failure mode. The measured local maximum vertical strain of the CFRP wrap was in the order of 0.0063 or 40% of ultimate. This value is not an absolute because it greatly depends on the location of the strain gage with respect to a crack. Load-strain relationships for the two strengthened beams are shown in Fig. 8. The strains at gauges 7, 9, and 10 are plotted. For both beams, shear cracking starts at the same load level; however, a much higher ultimate load (and strain) is attained for BT3.

Typical failure modes of the tested beams are shown in Fig. 9. No debonding was observed in the CFRP wrap of beam BT3 at ultimate capacity. After the beam failed in flexure, the CFRP wrap ruptured at the end of the shear crack near the support, as shown in Fig. 9(c). The load carrying capacity of beam BT3 was 442 KN with 145 and 42% increments over the reference beam BT1 and the equally strengthened beam BT2, respectively.

Experimental results in terms of load-mid span deflection of the three beams are shown in Fig. 10. This figure indicates that beam BT3 gained more stiffness and ductility than beam BT2. The additional ductility was obtained from the flexural failure mode. The mid-span deflection of beam BT3 at failure was about 3 times the deflection of beam BT2 at failure.

D. Design Consideration

Design algorithms for computing the contribution of externally bonded FRP to shear strength of RC beams have been proposed (Khalifa et al. 1998). Although the proposed algorithms do not specifically address the effect of the end anchorage, it is possible to extend them to include this case. Per ACI 318-98, the nominal shear strength of an RC section, is the sum of the shear strengths of concrete and steel shear reinforcement. For beams strengthened with externally bonded FRP reinforcement, the nominal shear strength may be computed by the addition of a third term to account for the contribution of FRP.

FRP without end anchorage: The equation to compute FRP contribution is similar to that for steel stirrups and consistent with ACI format. The ϕ factor for FRP contribution is lowered to 0.70 from 0.85. In the equation, an effective FRP stress, smaller than its

nominal strength, is used to replace the yield point of steel. The effective stress is computed by applying a reduction coefficient to the nominal FRP strength, which is dependent on the governing mode of failure. Failure is governed by either rupture of FRP reinforcement (at an average effective stress level below nominal strength due to stress concentrations), or debonding of the FRP reinforcement. In either case, an upper limit of the reduction coefficient is established in order to control shear crack width and loss of aggregate interlock. This limit is such that the ultimate strain in the FRP be less than 0.5% (including the ϕ factor).

In addition to the upper limit, two equations were proposed (one for each mode of failure) for the computation of the reduction factor (and thus the contribution of FRP). The lowest of the three reduction factors would control design. The computed design (including the ϕ factor) and experimental contributions of CFRP to shear strength for beam BT2 are equal to 56.5 and 65 KN, respectively.

FRP with end anchorage: For the case of U-wrap with end anchorage, the failure mode of FRP debonding is not to be considered. The reduction factor is only controlled by FRP rupture and the upper limit. Accordingly, the computed design (including the ϕ factor) and experimental contributions of CFRP to shear strength for beam BT3 are 72 and 131 KN, respectively. When compared to beam BT2, the use of the end anchor produces an increase of approximately 30% in design strength and a safety factor of 1.82 as opposed to 1.16.

6. Conclusions

Strengthening and rehabilitation of RC structural elements with externally bonded FRP composites is becoming an accepted technology. An innovative anchor system has been developed to allow a better exploitation of the potential of this technology. The U-anchor system provides an effective solution for cases in which the bonded length of FRP composites is not sufficient to develop its full capacity or where anchorage to adjacent members is required.

The U-anchor can be used with FRP sheets and pre-cured laminates that are unbonded or fully bonded to concrete. It is based on the idea of embedding into a preformed groove in the concrete (or masonry) a bent portion of the end (or near the end) of the FRP reinforcement. The discontinuity is filled with a viscous paste and may or may not include an FRP bar. In the case of sheets, the bent is created during wet lay-up and, in the case of laminates, the bent is pre-formed. The U-anchor is compatible with the FRP strengthening system and avoids high stress concentration and durability concerns

An example of experimental verification was discussed to show the feasibility and effectiveness of the proposed system in increasing the shear capacity of RC beams strengthened with CFRP U-wraps. For a beam strengthened with CFRP without U-anchor, shear capacity increased but failure was governed by debonding of the CFRP. In the specimen where the anchor was used, shear capacity of the member further increased and no FRP debonding was observed at ultimate.

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As additional validation work to fully characterize all possible U-anchor options continues, there is sufficient evidence to indicate that the novel U-anchor will make FRP strengthening even more attractive and economical for the concrete/masonry repair industry.

7. Acknowledgements

8. References

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Table 1 – Beam material properties

Material	Dimensions (mm)	Yield stress (MPa)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Concrete	----	----	35	----	----
Steel Reinforcing	D = 28	470	----	730	200
	D = 13	350	----	530	200
	D = 10	350	----	530	200
CFRP sheets*	t = 0.165	----	----	3,790	228

Note * = carbon fiber only
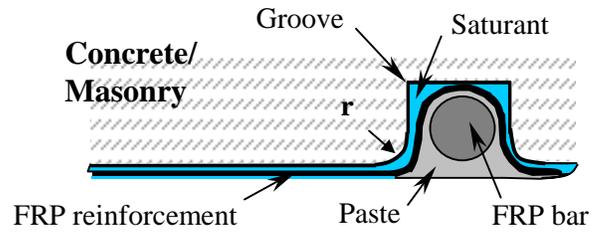
(a) Anchorage to plane surface
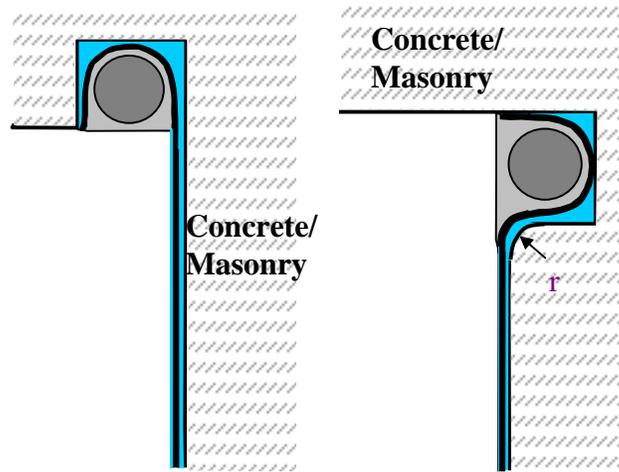
(b) After corner anchorage   (c) Before corner anchorage

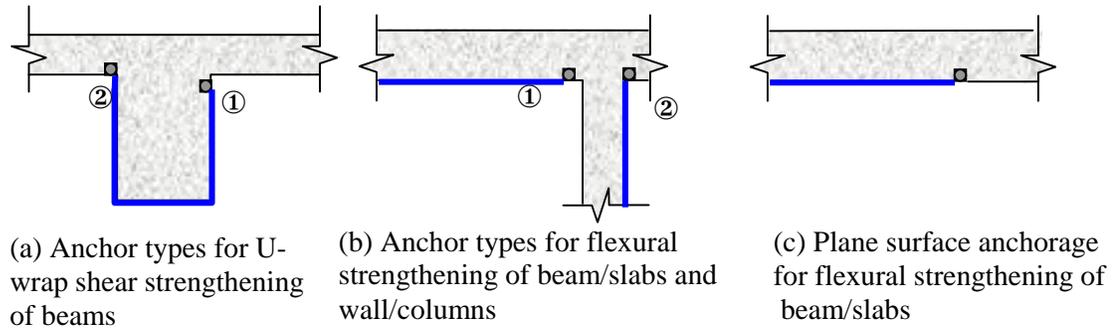**Fig. 1 – Different application schemes of the U-anchor**

(a) Anchor types for U-wrap shear strengthening of beams

(b) Anchor types for flexural strengthening of beam/slabs and wall/columns

(c) Plane surface anchorage for flexural strengthening of beam/slabs

Fig. 2- Examples of applications for anchorage system
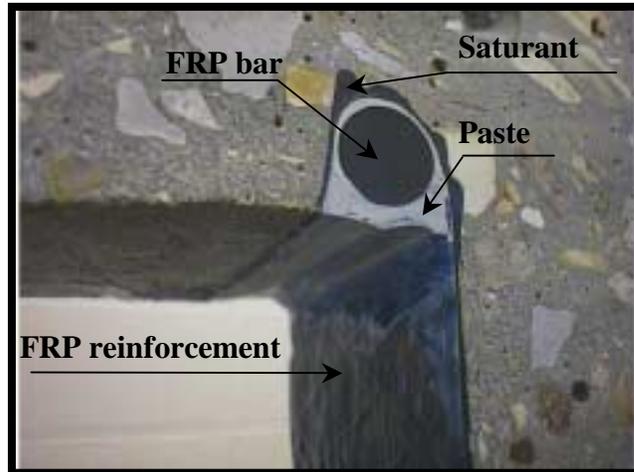
Fig. 3. Cross-section showing details of the U-anchor obtained by slicing a beam

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(a) Application of U-anchors
without FRP bar

(b) Application of U-anchors for
continuous FRP reinforcement
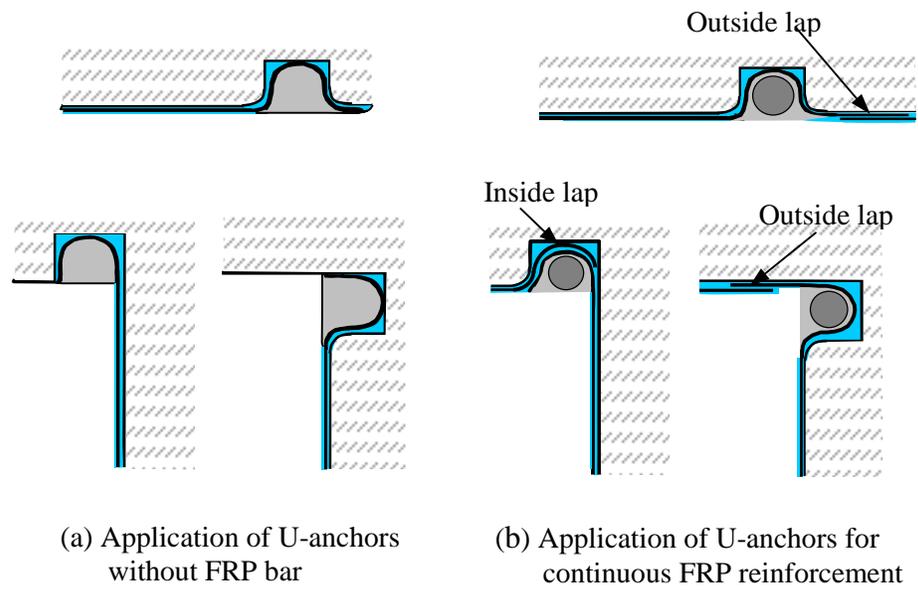
Fig. 4– Different application options for the proposed anchorage
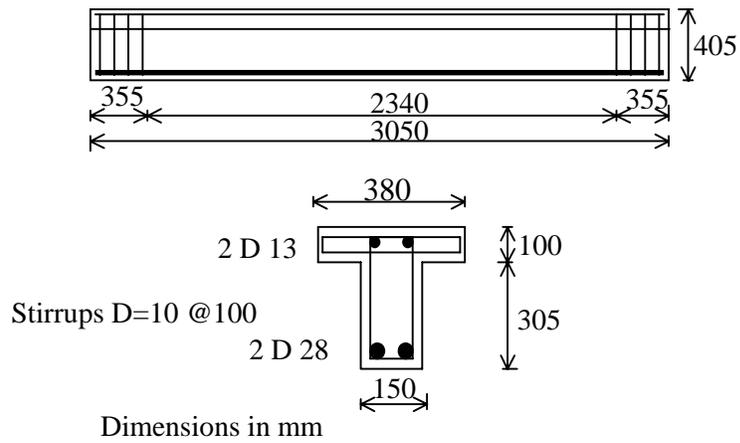
Fig. 5 - Beam specimens detailing and dimensions
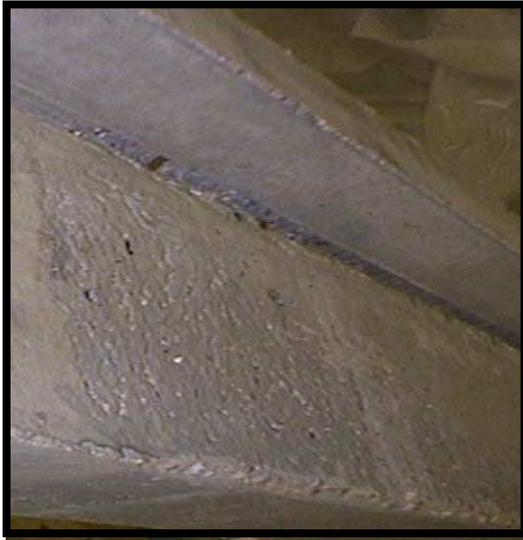
(a) Cutting a groove in the beam flange

(b) Applying CFRP sheet

(c) Inserting a glass FRP bar

(d) Filling the groove with epoxy paste
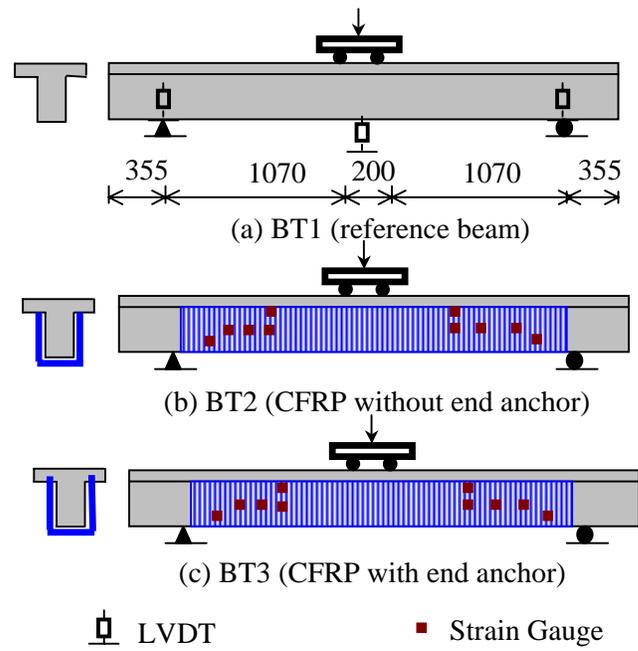
Fig. 6 - End anchor details for beam BT3

(a) BT1 (reference beam)

355   1070   200   1070   355

(b) BT2 (CFRP without end anchor)

(c) BT3 (CFRP with end anchor)

LVDT   ■ Strain Gauge
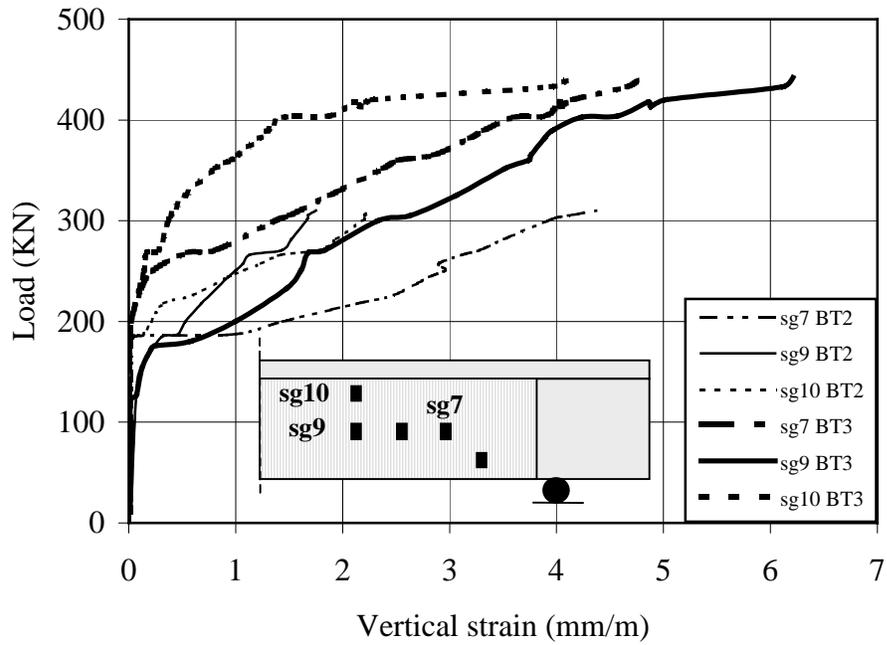
Fig. 7 - Test setup and strengthening schemes

Fig. 8 – Load vs. vertical strain in CFRP for beams BT2 and BT3

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(a) Beam BT1 (reference beam)

(b) Beam BT2 (CFRP without end anchors)

(c) Beam BT3 (CFRP with end anchors)

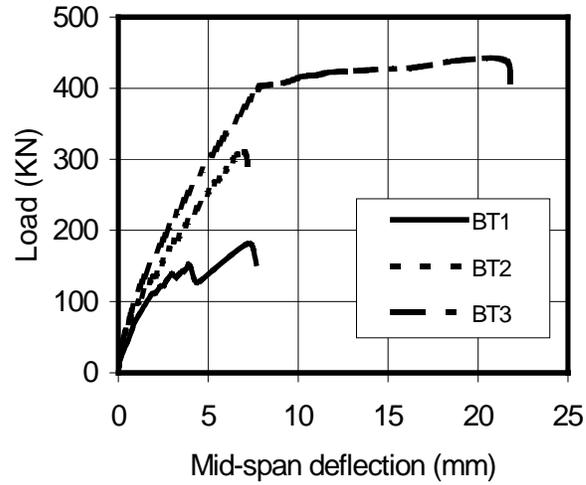**Fig. 9 -Failure modes of tested beams**

Fig. 10 - Experimental results in terms of load-mid span deflection