

# The Experimental Response Measurements of CFRP Retrofitted Shear Deficient RC Beams under Concentrated Load

Mohammad Zaman Kabir<sup>1</sup> and Erfan Shafei<sup>2</sup>

<sup>1</sup>Professor, <sup>2</sup> Former Ph. D student and currently acting as a faculty member at Uromieh University

<sup>1,2</sup>Department of Civil Engineering, Amir Kabir University of Technology, Tehran, Iran

**Abstract:** *The current experimental work deals with the response of intact and CFRP strengthened beams. The parameters such as strength and ductility are to be measured and compared between intact and retrofitted specimens. In this study six small-scale rectangular beams are tested under central concentrated loading. The scaling rule of construction preserves the physical similarity of the samples to the full-scale beams. The retrofit material is carbon fibre reinforced polymer (CFRP) in sheet form. The CFRP sheets wrap the external surface of four beams in two orientation types, unidirectional (UD) and cross-ply.*

*Based on the obtained results, the UD retrofit increases the shear strain of web at the failure moment, while the cross-ply retrofit increases the vertical strain rather than shear strain. The UD retrofit illustrates bending failure mode with local and deep flexural cracks, but the cross-ply retrofit causes simultaneous bending-shear failure with distribution of cracks in wider length.*

**Keywords:** Reinforced Concrete Beam; Shear Failure; CFRP Sheet Retrofit; Collapse Ductility

## 1. Introduction

Over-span wide diagonal cracks generate in shear-deficient RC beams, propagate toward load points and lead to rupture of transverse stirrups. Deep and common beam have shear span to effective depth ( $a/d$ ) ratios lower than two and higher than six respectively, which can resist the applied load within arch mechanism and flexure mechanisms after shear cracking of the web in that order. While variable angle web cracks generate in shear-deficient beams with  $a/d$  within previously mentioned limits, steel stirrups split along the crack path, rebar loose bond to concrete and member collapses in a fragile manner. The global stability is lost in beams without exploit of material ductility and the absorbed energy is chiefly degraded. The strength of such members can be restored using externally bonded fibre reinforced polymer (FRP) sheets, which efficiently mitigate concrete damage and stabilize flexural cracking along the span. Although steel and FRP sheet act as crack-restraining reinforcements, FRP remains linear elastic up to rupture dissimilar to steel which yields plastically. Undesired regular result of shear fracture is concrete-steel bond loss in beams which makes yielding of steel rebar unfeasible. FRP sheets have high strength-to-weight ratios than mild steel and can efficiently restrain opening of shear cracks and maintain steel-concrete bonding.

Recently conducted several investigations handle shear strength restoration of RC beams. Detailed experiments on typical beams with flexural and shear composite retrofits are conducted and the results are affirmed as semi-empirical design regulations [1, 2]. Täljsten [3] investigated the effect of FRP shear fabrics on the principal direction of inclined cracks along shear-span in typical beams with an experimental approach. Zhang and Hsu [4] tested CFRP-bonded beams without stirrups in order to measure collapse ductility. Colotti and Swamy [5] predicted ultimate load capacity of typical beams retrofitted with FRP plates in flexural and shear modes by analytical models. Haddad et al [6] investigated the response of FRP-strengthened beams with the intact shear failure mode in experimental program and measured the contribution of retrofit in strength

enrichment. Noël and Soudki [7] lately estimated the crack widths of FRP-bonded typical beams with and without steel stirrups and proposed the relation of shear and flexural crack widths.

The current study deals with shear-deficient beam response and the retrofitting mechanism of FRP sheet. The focus is on the deformation distribution between materials along the response stages of intact and strengthened samples and the failure patterns. The first effort is to construct practical specimens with domination of shear-type physical mechanism and then thoroughly wrap them with unidirectional (UD) and cross-ply FRP sheets. Records consist of resisting force and resultant deflection of beams that are loading monotonically in three-point flexure test setup.

## 2. Experimental Procedure

Concrete mixture has 0.6:1:2.4:1.9 weight proportions with 10mm maximum aggregate size according to ACI 211.1 guides [8] and satisfies dimensionless concrete strength requirement. Table 1 expresses the details of mixture design for the six small-scale beams and the two standard cylinders for each beam.

TABLE I: Details of Concrete Mixture used for Specimen Preparation

Characteristic	Value
Expected Crushing Strength	24(MPa)
Cement Type	Regular Portland
Slump	90 (mm)
Free-Water Content	188(kg/m <sup>3</sup> )
Cement Content	300(kg/m <sup>3</sup> )
Gravel Content / Density / Absorption	728 (kg/m <sup>3</sup> ) / 1620 (kg/m <sup>3</sup> ) / 0.5%
Sand Content / Density / Absorption	560 (kg/m <sup>3</sup> ) / 2610 (kg/m <sup>3</sup> ) / 0.7%
Water-to-Cement Ratio	63%

Water curing in 17°C warmth for 28 days provides the average modulus as 20.2GPa, strength as 25.5MPa, and crushing strain as 0.23% for the concrete samples. The flexural reinforcement is D12 rebar with 603MPa yield stress at each corner and the shear stirrup is a D3 rectangular tie with 390MPa yield stress at 50mm spacing in order to satisfy dimensionless steel strengths respectively.

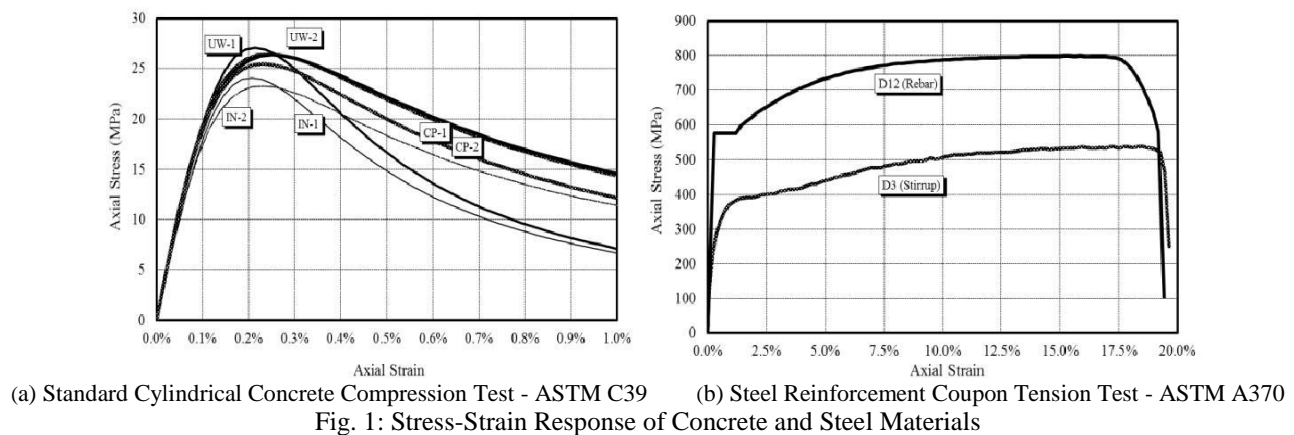


Figure 1 demonstrates the stress-strain response of cylindrical concrete and steel reinforcements. Two external 8mm-thick plates, anchor the longitudinal rebar and bond them to concrete in shear-critical beams.

Constructed beams have three categories as intact (IN), unidirectional sheet wrapped (UW) and cross-ply sheet wrapped (CP) and strengthening sheet is a carbon fibre reinforced polymer (CFRP) sheet with 0.17 mm thickness. Wrapping of CP and UW beams consists of three 700×500mm sheets with fibres parallel to height (90°) in first ply. In addition, CP beams have one 1200×500mm sheet with fibres parallel to span in second ply that forms cross-ply (0°/90°). The overlap length of each CFRP sheet is 150mm according to the regulation of ACI 440.2 code [9] to facilitate sufficient bonding of composite. Thermo-set epoxy resin bonds the CFRP lay-up to grind the concrete surface with 1.0 mm overall thickness as the manufacturer recommends in order to provide

the required strength. Figure 2 expresses the layout of intact and retrofitted specimens and the Table 2 summarizes test-acquired material properties.

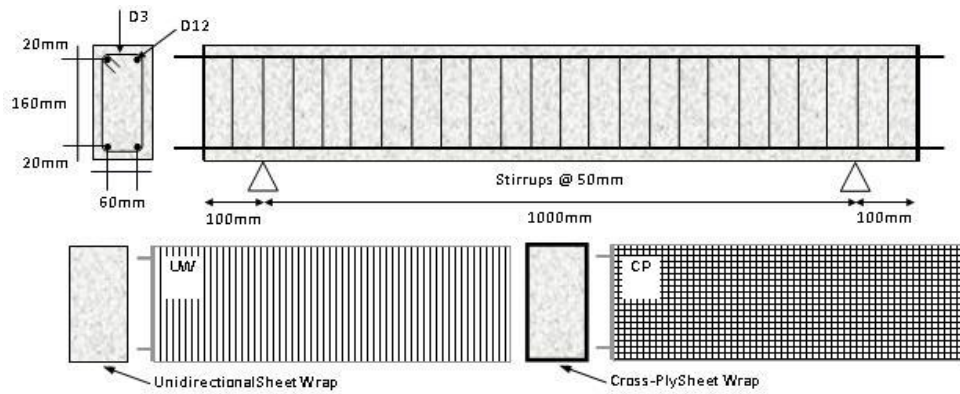
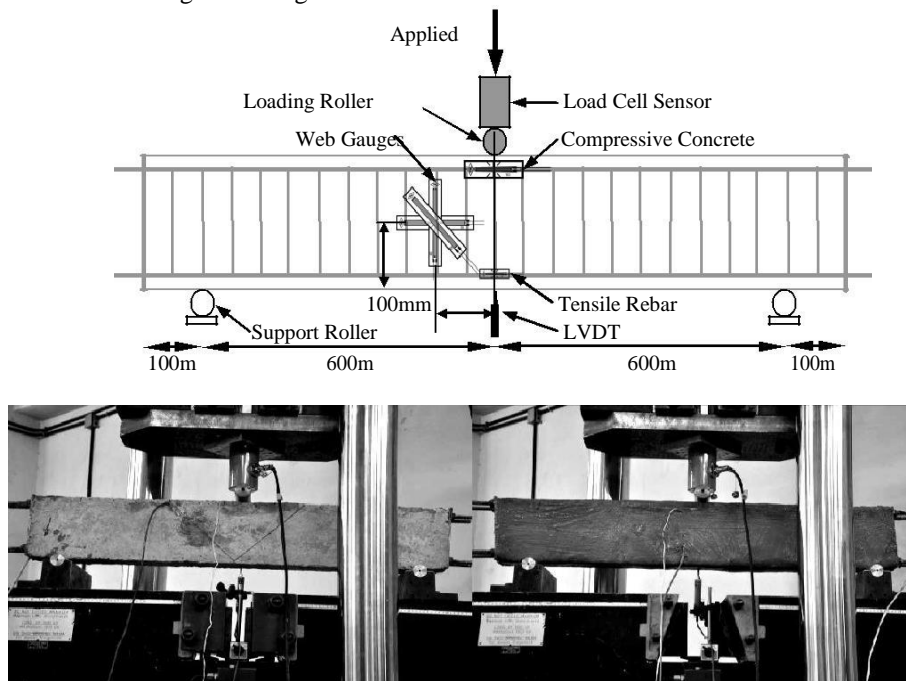


Fig. 2: Configuration and Reinforcement Details of RC Beams



Intact Specimen (IN) Strengthened Specimen (UW & CP)  
Fig. 3: Demonstration of Test Setup and Instrumentation of Intact and Strengthened Specimens

A 1000kN universal servo-hydraulic test machine bends the constructed beams in three-point mode as defined by the ASTM C293 [10] guides with 0.025mm/sec monotonic increase of mid-span deflection. Figure 3 shows the detailed layout of instrumentations and test setup of RC beams. An external 500kN static load cell unit with a steel roller mount has contact with the beam top and measures the resisted load. In order to determine the elastic stiffness of specimens and ensure uniform support contact, system applies three progressive 7kN load cycles at the outset of the test. A 100mm-stroke linear variable differential transformer (LVDT) attached to the bottom surface of beams measures the mid-span deflection.

### 3. Global Response Results

The observed responses are rupturing, yielding and hardening for IN, UW and CP beams, respectively, at the onset of failure. Figure 4 plots the resisted load curves versus mid-span deflection for each specimen and Table 2 summarizes the peak resisted load ( $P_u$ ), failure deflection ( $\delta_u$ ) and initial stiffness ( $D$ ). The failure deflection is the mid-span displacement when the resisted load decreases by  $0.2P_u$ . Further, the ductility factor is the ratio of

$\delta_u$  to the yield deflection ( $P_u / D$ ) and demonstrates the plastic flexibility of beams. Intact beam (IN) curves have an almost linear path up to 82kN peak load with low ductility of 1.6 and then sharply soften due to catastrophic shear fracture. The shape of the curve indicates ignorable flexural cracking before the dominant shear fracture.

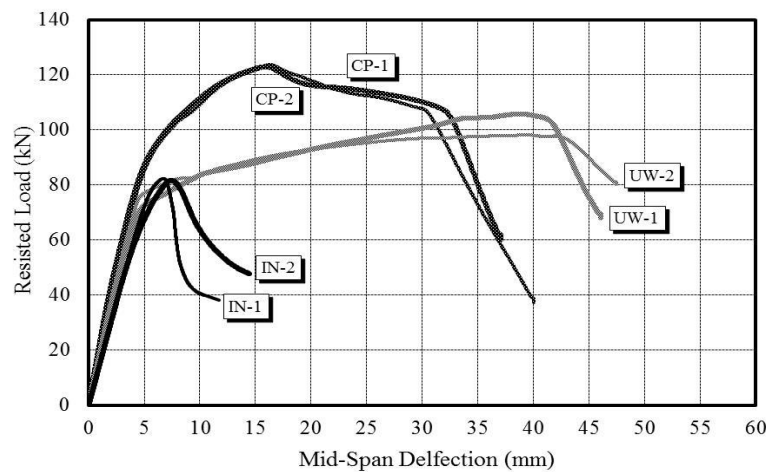


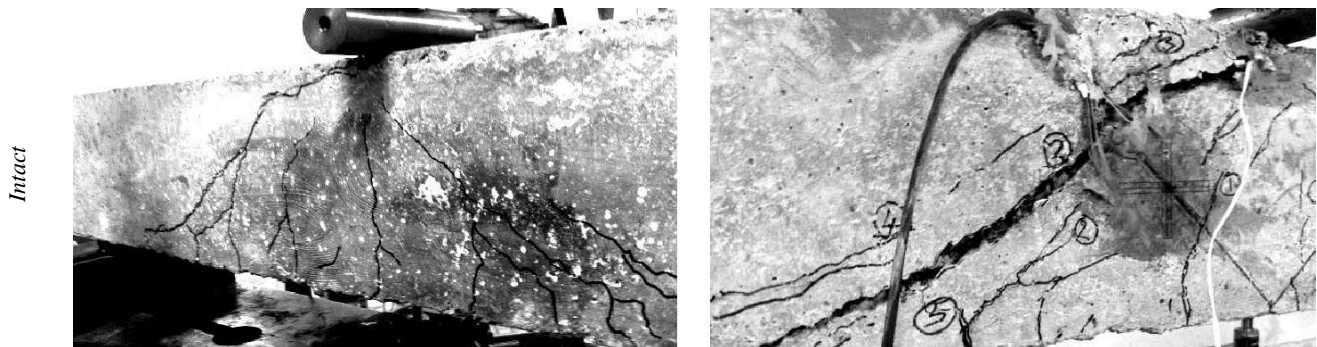
Fig. 4: Resisted Load versus Deflection Curves of Beams

The curves of unidirectional-wrapped beam (UW) have clear slope change prior to peak load when the rebar yields and compressive concrete dilates. The curves harden up to 102kN peak load with sensibly high ductility of 8.4. The crushing process of CFRP-confined concrete provides the hardening stiffness as 7% of initial stiffness. Finally, the curves of cross-ply-wrap beam (CP) slightly hardening as longitudinal CFRP fibres elongate. The 120kN peak load and ductility factor of 5.8 indicate the parallel enhancement of strength and flexibility.

TABLE II: Response Characteristics of Tested Specimens

Specimen	Initial Stiffness – $D$ (kN/mm)	Peak Resisted Load – $P_u$ (kN)	Failure Deflection $\delta_u$ (mm)	Strength Enhancement	Ductility Enhancement
IN-1	15.2	82.3	7.7	-	-
IN-2	14.9	81.7	9.7	-	-
UW-1	19.1	98.1	43.4	1.20	5.56
UW-2	18.5	105.5	47.5	1.29	5.49
CP-1	21.6	123.6	31.7	1.51	2.29
CP-2	21.4	116.9	33.3	1.43	2.28

The failure pattern of intact and retrofitted RC beams is essential for the determination of the governing response. Figure 5 shows the failure modes of test beams and the numbered cracking sequence. Early diagonal cracks of IN beam initiate in the middle of shear span and then propagate toward load points.



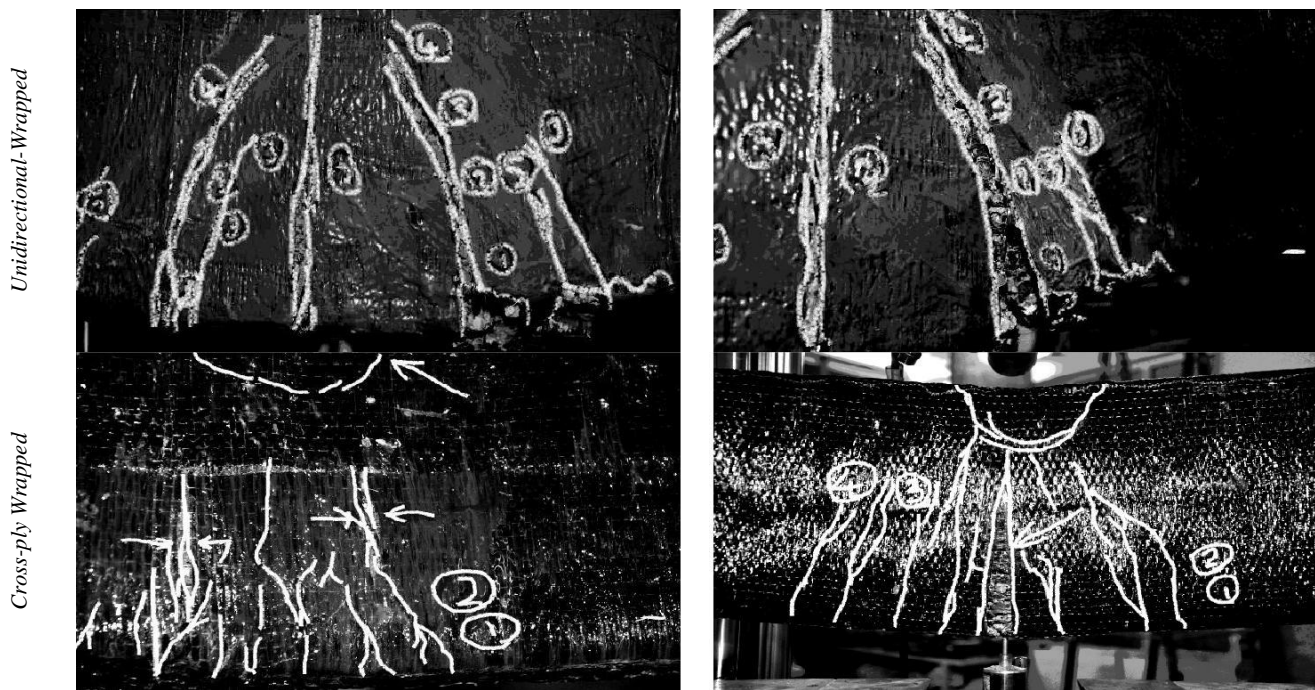


Fig. 5: Failure Modes of intact and CFRP retrofitted RC Beams

The adjacent inclined cracks merge and form major wide shear cracks that rupture the steel stirrups and cause the rebar-concrete bond loss. The IN beams collapse as soon as major shear cracks reach load points and the result is severe span-over damage. The flexural resin cracks form in UW beams at the mid-span location as rebar yields. Then the dilation of CFRP-confined compressive concrete accelerates the flexural-crack propagation along the beam height and length. The collapse mechanism of UW beams consists of concrete crushing, rupture of CFRP fibres in bottom surface and stirrup yielding in the mid-span region. CP beams have less flexural cracks than other beams because of the high stiffness of longitudinal CFRP fibres. Then the flexural-shear cracks initiate in beam height and rupture the longitudinal fibres along the crack path. In CP beams, the height of cracks and the dilation of confined concrete is less than UW beams, but the length distribution of cracks is higher. The collapse process of CP beams contains progressive rupture of longitudinal fibres, splitting of cross-ply fibres in beam web and yielding of stirrups

#### 4. Concluding Remarks

Characteristics of shear-deficient scaled simple-supported rectangular RC beams (preserving physical similarity) in both intact and CFRP retrofitted cases are experimentally studied. Fibre strengthening schemes considering unidirectional and cross-ply span-over complete wraps are the targets affecting global and local responses of testing samples and activating flexural mode. Results reveal significant strength and ductility enhancements as functions of applied composite stacking type altering field and feature of deformation along possible failure locations. Unidirectional and cross-ply schemes have 24% and 47% ultimate strength increase rates and 450% and 130% collapse ductility improvements in that order. Test load curves retain yielding and hardening features due to confining effect of vertical and flexural stiffness of horizontal fibres, respectively. Outcomes extracted from the current investigation program are as following points:

- Based on the global response scaling relation on the brittle fracture response of concrete material effectively satisfies the dominant physical similarity in prototype and model beam samples with initial shear failure modes.
- Shear failure does not allow distribution of flexural cracks in intact samples and therefore intensifies the brittleness of collapse mechanisms, although, flexural-to-shear strength ratio is near unity and steel stirrups rupture. However, strengthening procedures have advantages as plastic hinge formation and concrete crush strain recovery.

- Generated plastic hinge region length in cross-ply CFRP retrofit is almost half of the analogous case in vertical fibre orientation due to provided flexural and doubled shear stiffness aspects. Failures in composite laminate are in form of vertical fibre rupture along mid-span bottom surfaces and adjacent mid-height web regions. In addition, horizontal carbon fibres in cross-ply case accelerate the failure of vertical ones due to the severity of distortional deformation.
- Composite retrofitted members almost have response feature alterations near 70% of their ultimate load-carrying capacity points where tensile steels extents intensively and adjacent concrete cracks.
- Both strengthening schemes cause yielding of horizontal rebar waiving catastrophic failure mode as initially occurs in intact samples. The failure point curvature at mid-span, location enhances by 10 ratio in unidirectional fibre stacking with respect to intact case, providing both confining and yielding ductility with limited strength improvement, but cross-ply case improves the strength and ductility in a parallel manner.

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