

# Repairing & Strengthening Earthquake Damaged RC Beams with Composites

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**Abstract**—The dominant judgment for earthquake damaged reinforced concrete (RC) structures is to rebuild them with the new ones. Consequently, this paper estimates if there is chance to repair earthquake RC beams and obtain economical contribution to modern day society. Therefore, the totally damaged (damaged in shear under cyclic load) reinforced concrete (RC) beams repaired and strengthened by externally bonded carbon fibre reinforced polymer (CFRP) strips in this study. Four specimens, apart from the reference beam, were separated into two distinct groups. Two experimental beams in the first group primarily tested up to failure then appropriately repaired and strengthened with CFRP strips. Two undamaged specimens from the second group were not repaired but strengthened by the identical strengthening scheme as the first group for comparison. This study studies whether earthquake damaged RC beams that have been repaired and strengthened will validate similar strength and behavior to equally strengthened, undamaged RC beams. Accordingly, a strength correspondence according to strengthened specimens was acquired for the repaired and strengthened specimens. Test results confirmed that repair and strengthening, which were estimated in the experimental program, were effective for the specimens with the cracking patterns considered in the experimental program.

**Keywords**—Shear Strengthening, Repairing, CFRP Strips.

## I. INTRODUCTION

THERE is a common thought for earthquake damaged RC structures that replacing the building with the new one is more reliable instead of repairing them. This is because of the insufficient data in literature that indicates repairing & strengthening is adequate if it is done properly. This paper deals with this fact.

Cracks, concrete spalling and large deflections result in the deviation of structures from their designed strengths. It is clear that structures should be repaired in order to eliminate these deteriorations. In some cases, repair of structures is not sufficient alone for obtaining the expected features as a consequence it is necessary to strengthen the structures. However, a proper chosen repair technique increases the proposed service-life, restores or increases its strength and stiffness, guarantees the safety and serviceability, protects reinforcing steel bars from exterior effects, and finally improves structure's durability. Nevertheless only small number of studies was encountered in literature which investigates and/or examines that considerable and critical

subject, repairing and/or strengthening of flexural-damaged specimens with CFRP [1]-[3]. In addition, not many studies were scrutinized the efficiency of CFRP on repairing and/or strengthening of shear-damaged RC beams [4]-[6]. Besides, monotonic loading was applied in all the previous studies and the performance of repaired and CFRP strengthened specimens was not investigated under cyclic loads, which act like earthquake to the structure. Therefore the behavior, cracking pattern, deflection, ultimate capacities and failure modes of the repaired and then strengthened structures have to be evaluated. Besides, the factors which influence the behavior have to be laid bare for assisting the designers for further executions.

Although any case studies have not found in literature about repair & strengthening of earthquake-damaged (damaged in shear under cyclic load) RC beams, the main aim of this experimental work was to investigate the behavior and failure modes of repaired & strengthened RC beams. Therefore, four specimens, apart from the reference beam, were separated into two distinct groups for evaluation. Two experimental beams in the first group subjected to cyclic load up to failure then properly repaired and CFRP strengthened. Undamaged specimens, two, specimens from the second group, were strengthened with the identical strengthening schemes of repaired & strengthened specimens for comparison

## II. PROPERTIES OF MATERIALS

To reach correspondence in strength, a single concrete mix was used for all specimens. The concrete was a mixture of water, cement, sand and aggregate with the ratio of 0.68:1:2:3 by mass. The average compressive strengths of 28-day concrete cylinder were approximately 25MPa.

For all specimens, standard deformed reinforcement steel bars with a characteristic strength of 414MPa and elastic modulus of 205GPa were used as longitudinal reinforcement. 6mm bars with a characteristic strength of 275MPa and an elastic modulus of 192GPa were used for the shear reinforcement outside the shear span. .

## III. DETAILS OF TEST SPECIMENS

SPEC-1 was the reference of shear deficient beams', was tested without strengthening, and used as a baseline comparison to evaluate the contribution of strengthening material to shear capacity. Specimen will also refer to the repaired & strengthened specimens.

Specimens, apart from the reference beam, have been evaluated in two separate groups. Two specimens in the first

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group were initially tested up to failure. It was aimed to evaluate the behavior of RC beams with different damage degree. To acquire different damage form and degree, one specimen was tested without strengthening. It was planned to obtain the damage within the limits permitted by ACI 224 committee report [8]. One major and both large and small cracks was observed for the specimen. Remaining was tested after strengthening. Photos of the collapsed specimens are presented in Fig. 1. SPEC-3, which shear damage was limited with one major and both large and small scaled cracks, were strengthened with side-bonded CFRP strips. As the tension and compression face of SPEC-2 was heavily damaged, specimens were wrapped to obstruct similar cracking pattern after strengthening. CFRP spacing was ideal to hinder crack propagation [7].

Undamaged specimens, two specimens, Spec-4 and Spec-5, from the second group, were strengthened with the identical strengthening schemes of repaired & strengthened specimens for comparison [10]. The details of different ways of strengthening schemes are presented in Fig. 2

#### IV. EXPERIMENTAL STUDY

All specimens were tested under cyclic loading. To perform cyclic load to the specimen, a loading column was designed with hinges by the beam's free end. Loading column contained two hinges, a load cell and a hydraulic jack. The capacity of the hydraulic jack was 500kN while the load cell's capacity was 400kN with 0.06% linearity. Load was applied in cycles of loading and unloading. Load cycles were selected as they will help to evaluate the flexure and shear crack propagations and their affect to behavior. Loading was increased up to yield of flexural reinforcements or until the failure of the specimen. Four linear variable differential transformers (LVDTs) were used to monitor displacements. The LVDT's are located at the end of the beam for maximum displacement, under the rigid support to calculate the undesired displacement and finally on the rigid support to calculate the rotation. A schematic view of experimental set-up is shown in Fig. 3.

#### V. REPAIRING AND STRENGTHENING PROCEDURE

##### A. Epoxy Injection Technique

The repairing process was started with purifying the damaged-beam with compressed air. Right after that treatment, the damage degree of the cracks became observable. Thereafter, determined spalled and damaged concrete was chipped out from the beam body. Pieced cracks that are in a manner which cannot be cured with epoxy, especially at the tension and compression face was filled with SikaMonoTop620. Afterwards, injection nipples were installed along the cracks at about 200mm centers on both sides of the beam. Sikadur30 was used to fix the injection nipples as well as to seal the small scaled surface cracks. After designating that the cracks were properly sealed, the surface of the beam was leveled until obtaining the original shape and dimensions.

The injection of low viscosing epoxy, Sikadur52, was fulfilled when the cure period of Sikadur30 was finalized. A special hydraulic pump was used for injection. During the injection process a constant pressure, which do not cause additional damage to the existing cracks, was provided. The epoxy injection was started from the lowest nipple and carried on until the epoxy was executed from the above nipple. Thereafter, the lower injection nipple was capped and the injection was carried out from the above nipple. The process was repeated for each nipple until designating that the epoxy completely filled the crack. After drying of the injected epoxy, all nipples were removed from the beam surface.

##### B. CFRP and EPOXY Adhesive

SikaWrap 230c (unidirectional) CFRP sheets were used for strengthening and Sikadur-330 was used as adhesive. Two different surface preparation procedures were carried out before attaching the CFRP strips. The surface of the specimens, which were repaired & strengthened, was almost covered with epoxy; actually there is no need for sand blasting for these specimens. Notwithstanding, the surface was leveled and concrete parts without epoxy were sand blasted [9]. Apart from the first application, the undamaged specimens' outer weak surface of the concrete was properly removed with sand blasting. Afterwards, loose particles on the surface of the specimens were cleaned with compressed air to prepare the specimens for bonding. Bonding procedure was entirely identical for all specimens. The epoxy resin was mixed in accordance with manufacturer's directions and applied on the prepared concrete surface and to CFRP strips. Afterwards, CFRP laminates were attached at the designated places and a roller was used to guarantee impregnation of the sheets by the resin. Thereafter, another layer of epoxy was put on top of the fabric and the excess epoxy was removed. Finally, the system was left for curing at room temperature for at least three weeks before testing. The humidity ratio at the laboratory was measured throughout the curing period with hygrometer. It was checked to decide whether humidity was influencing the strengthening period or not. The same strengthening procedure was carried out for all strengthened specimens.



Fig. 1 Photos of the Collapsed Specimens

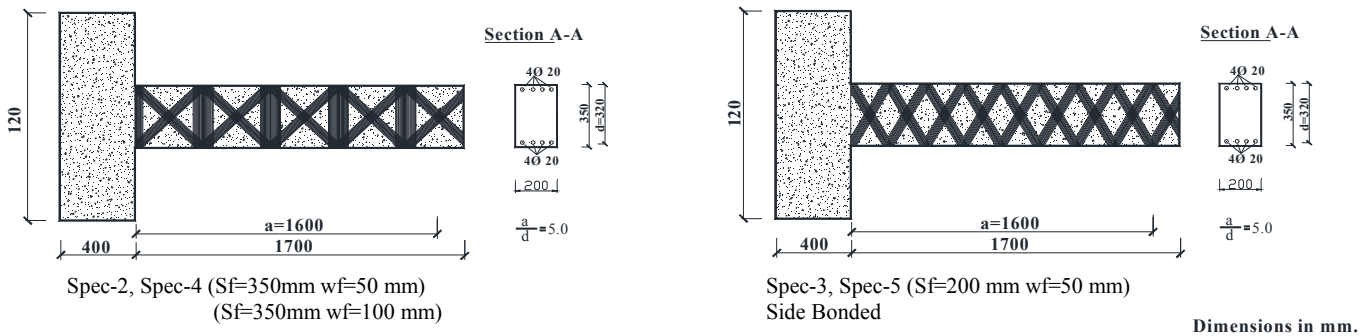


Fig. 2 CFRP Arrangements for Specimen Beams

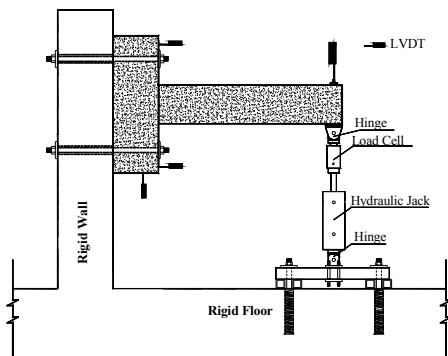


Fig. 3 Test Setup and Instrumentation

## VI. OBSERVED BEHAVIOR AND FAILURE MODES

To designate the experimental work's success, repaired & strengthened specimens' behavior was primarily compared with SPEC-1, unstrengthened and initially uncracked control specimen. SPEC-1 was failed in shear due to critical shear crack propagation at -61.90kN load level. In all tests, repaired specimens reached and exceeded the strength of control beam and furthermore showed better behavior.

SPEC-2 was strengthened by considering that the tension face was heavily damaged and a main crack at the beam body was situated. In this instance, inclined CFRP strips in which vertical CFRP strips were wrapped the beam at the overlapping regions was preferred for strengthening. Although the beam was heavily damaged, beam behavior was developed by the evaluated repair and CFRP strengthening technique.

Longitudinal compressive and tension reinforcements of the beam were reached at their yield strengths at 106.33kN and -105.21kN load, respectively. Specimen was constrained and finished two more load cycles after the yield of the longitudinal reinforcements. However, localization of shear cracks at a section compelled the strips to higher stresses that they can resist and right after CFRP strips were ruptured at -103.82kN load level. As the strengthened part lost its resistance against shear, critical shear crack propagation was materialized abruptly at the decayed section as can be seen from Fig. 4 (a). The repaired main crack was endured until the rupture but abandoned and heavily damaged right after the failure occurrence. The behavior of SPEC-4 did not bear a resemblance to SPEC-3. In spite of the new load cycles that were exposed to the SPEC-4, no significant increase on the number and size of cracks has seen after the yield of the longitudinal reinforcements. In addition, the new propagated and previously developed shear cracks did not intensify at a section. Therefore, CFRP strips were not compelled under increasing stresses as much as SPEC-2. As the specimen's behavior was reliable, a plastic hinge was formed between the supporting base and all through the cross section of the beam. This resulted in a ductile beam, which is able to undergo visible deflection without losing its load carrying capacity (Fig. 4).

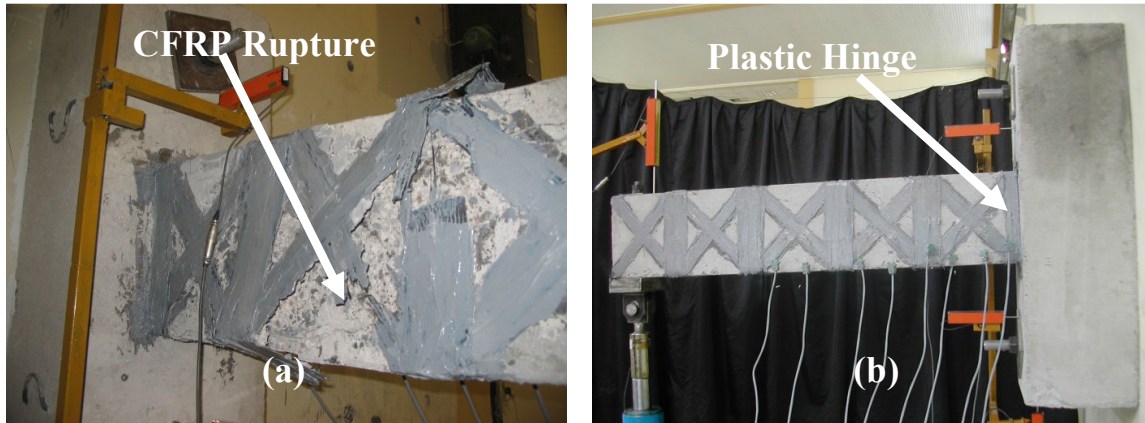


Fig. 4 Failure modes of Specimens

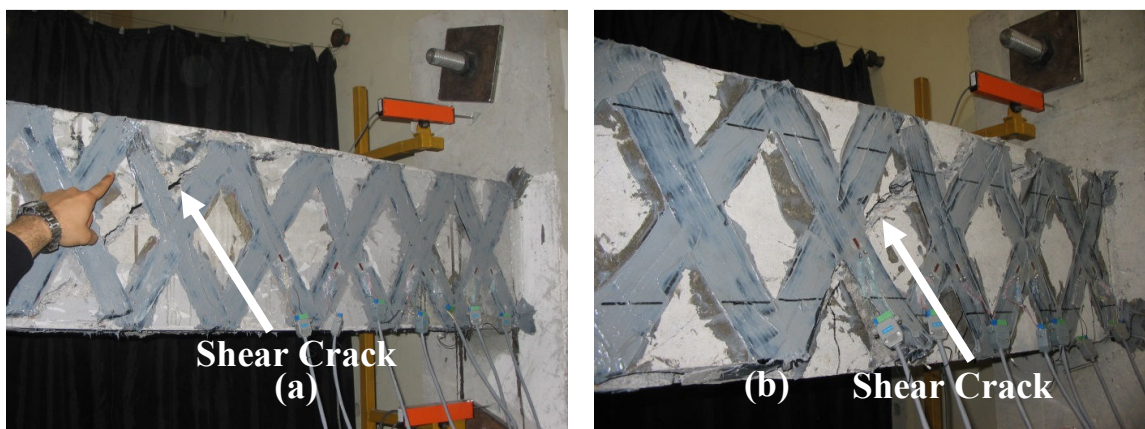


Fig. 5 Failure modes of Specimens

SPEC-3 and SPEC-5 showed similar behavior and strength when tested. The only distinction between these specimens is the region where the main shear cracks were advanced. Various shear cracks were developed at the shear span until completing the 90 kN load level but none of these cracks were critical. However, during the forward loading step of 90 kN load cycle, both large and small scaled shear cracks were intensified between the fifth inclined cross and the sixth inclined cross. There after specimen strength was decreased %1. Notwithstanding, an increase at strength was observed and specimen straightened up that unconscious state without failure. As the load increased, small scaled cracks' length and wideness was increased at once and that cause the specimen to fail in shear at 93.92 kN load level (Fig. 5 (a)). Shear cracks were not propagated at a specific section but all throughout the shear span for SPEC-5. Besides, less shear crack propagations were also observed according to SPEC-3. It was expected that specimen behavior will be directed to flexural while testing. However, at 97.31 kN load level main shear crack, which was developed between the third inclined cross and the fourth inclined cross, was advanced abruptly and caused the beam to fail in shear as seen from Fig. 5.

According to test results, the repair technique that was selected in the experimental program is capable of restoring the ultimate capacity of the earthquake-damaged RC beams. The contribution of strengthening material to shear capacity of the strengthened specimens can be seen from Table I.

Accordingly, CFRP usage exhibited satisfying increase at load-carrying capacity. All CFRP applications were increased the strength and behavior of the undamaged strengthened specimens' in different manner. But behavior similarity was observed for the repaired and unrepaired specimens. That proves the success of repairing procedure.

TABLE I  
EXPERIMENTAL RESULTS

Specimen #	Cracking Load (kN)	Flexural Yield Load (kN)	Failure Load (kN)	Stiffness at Yield (kN/mm) (8)	Ductility Ratio (9)	Increase in Ultimate Strength (10)	Failure Mode at Ultimate (11)
(1)	Flexure (2)	(3)	(4)				
Specimen-1 Control	39.2	----	-61.9	----	----	----	Shear
Specimen -2 Repaired& Strengthened	33.1	106.3	-103.8	3.72	1.92	1.72	Flexure-Shear
Specimen -3 Repaired& Strengthened	24.8	----	93.9	----	----	1.52	Shear
Specimen -4 Strengthened	-37.5	106.5	107.5	4.57	1.99	1.72	Flexure
Specimen -5 Strengthened	36.6	----	97.3	----	----	1.57	Shear

\*Forward loading step was described with positive mark and backward loading step was described with negative mark in Table I

## VII. CONCLUSION

In the experimental program, the behavior and failure modes of earthquake-damaged RC beams were investigated. Tests results indicated that repair and strengthening technique is capable of restoring the ultimate capacity of the earthquake-damaged RC beams.

- A strength similarity with a distinction of 4% according to references was obtained for the repaired & strengthened specimens. Accordingly, the evaluated method in the experimental program has the ability of advancing the behavior of earth-quake damaged RC beams to resembling level [11].
- The evaluated technique was behaved enormously prosperous that the crack patterns of repaired specimens were entirely changed according to the prior crack patterns. Additionally, the failure of the repaired specimen was materialized because of the new cracks that have been developed on a section other than that of the critical ones were situated.
- The behavior of the specimens, which were failed due to concrete cover separation while initial testing, was developed after wrapping. Besides, initially occurred failure was obstructed. In this instance, choosing the right strengthening scheme by considering the initially materialized failure mode is essential for improving the behavior.
- The beams that are repaired & strengthened after being brought to original position have the yield stiffness' of repaired & strengthened specimens were decreased to up to 23% when compared with the strengthened reference specimens. Accordingly, strengthening material was not contributed effectively for increasing the initial stiffness' and the yield stiffness' of repaired specimen.
- As mechanical anchorage usage could produce extra harm to the specimens, it was not preferred to be performed to the earthquake-damaged RC beams in the experimental program.

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