Flexural behavior of self-compacting damaged reinforced concrete box beams strengthening with CFRP

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Abstract. Fibre Reinforced Polymer (FRP) materials appear to offer an acceptable solution for the upgrading and repair of concrete structures based on the advantages associated with these compounds. This paper presents an experimental analysis of strengthening in damaged R.C. box beams based on gluing CFRP sheets to the members. The main objective was to study the flexural behaviours of damaged R.C. box beams strengthened with CFRP sheets, and ten simply supported box beam specimens were thus tested under a monotonic two-line load. Variables investigated included the configuration of CFRP sheets used and the damage ratios (45%, 60%, and 75%). The tested box beams were designed according to ACI 318M-14 to ensure flexural failure. The study showed that adding composite fibre sheets used as External Bonding (EB) technology can offer a convenient and effective strengthening method for damaged concrete structures. The results further showed that side strengthening (extending the sheet under the beam with both sides facing each other) provided an effective tool for increasing the ultimate load capacity by over 28% on average as compared to other methods, while increasing the deflection ratio by over 40%. The behaviour of each box beam was examined with respect to the first crack load, ultimate load, crack pattern, and load-deflection, and carbon fabrics were shown play a major role in the repair of box beams.

Keywords: CFRP, Strengthening, Damage, Box beam, Self-compacting, Flexural behaviour.

1. Introduction
The rapid development of concrete and construction techniques have led to new types of concrete, such as self-compacting concrete (SCC), emerging. This technique allows self-flowing concrete without the need for any mechanical vibration; the quality of SCC thus depends on liquidity without segregation, and this type of concrete can be used in places where it is difficult or impossible to use mechanical pressure, such as for underwater formwork, site stack foundations, columns, machine bases, or walls with crowded reinforcement (Khayat et al. [1]). SCC mixtures contain similar components to those
used in vibratory concrete, but with a higher ratio of fine materials such as silica fume and some additional chemical additives (Kim et al. [2]; Domone et al. [3]).

Many structures that have been in use for several years have suffered from a decrease in capacity due to steel corrosion, concrete cracking, or seismic damage. In recent decades, the use of Fibre Reinforced Polymer (FRP) materials has been promoted as an acceptable solution for the upgrading and repair of such concrete structures due to the many advantages associated with these compounds. There are three main types of FRP used for strengthening Reinforced Concrete (R.C.) structures: Aramid Fibre Reinforced Polymer (AFRP), Glass Fibre Reinforced Polymer (GFRP), and Carbon Fibre Reinforced Polymer (CFRP). CFRP has, however, been found to be the most effective for increasing the capacity of R.C. beams (Li et al. [4]; Abdel-jaber et al. [5]; Feng and Yuan [6]).

Several researchers thus have undertaken experimental studies of CFRP. R.C. beam flexural behaviours were found to be improved by CFRP modulation by Modena and Pellegrino [7], who investigated the flexural behaviours of both R.C. and Pre-stressed Reinforced Concrete (P.R.C.) beams strengthened with external pre-tensioned CFRP laminates. Independently bound CFRP stabilisation can be done using various methods, including varying end anchoring systems, and pre-stress transitions. The ultimate ability increases differ based on several parameters, including the mechanical anchor systems, which can notably increase the ultimate ability with regard to delaying delamination in structural components, increasing the ultimate ability of the structural elements, increasing the load at which first cracking occurs, and decreasing the amplitudes of cracks. Obaidat et al. [8] performed experimental work to investigate the behaviour of structurally damaged broadband reinforced concrete beams after the addition of CFRP. Several variables, such as internal reinforcement ratio, location, and length of CFRP were studied, and the increase in the maximum load of the modified samples was between 7% and 33% for the retrofits at flexure. The crack width for the modified beam notches also decreased as compared to that in the control beams.

Mosallam et al. [9] tested R.C. beams to assess the flexural behaviours of pre-loaded R.C. structured with pre-tensioned (pre-stressed) CFRP laminates, with several influencing experimental conditions considered, including: (i) pre-tensioned strain level, (ii) CFRP reinforcement ratio, and (iii) sustained loading level. Their experimental research indicated that both pre-tensioning strain and CFRP reinforcement ratio had major effects on the flexural strength and rigidity of the enriched beams.

Hassan and Abass [10] performed an experimental flexural evaluation of the strengthening of R.C. wide beams with different widths of CFRP. The variables considered included the amount of strengthening relative to the cross-section width of the beam at ratios of 30, 60, and 100%, respectively. The test results showed that the strengthened beam with 60% ratios provided the best flexural capacity, increasing flexural capacity by up to 29% as compared with that of the control beam.

Al-Sarraf et al. [11] undertook a performance investigation of the flexural behaviours of self-compacting R.C. Continuous Beams reinforced with CFRP Sheets. The experimental variables included the placement of CFRP sheets, the types of anchor, and the anchor positions. The results showed that CFRP strengthened external beams provided an improvement in ultimate load of 60.71%. The use of CFRP sheets to strengthen the continuous beams of reinforced self-compacting concrete was particularly effective in increasing the initial cracking load, and ultimate load.

Abdalla et al. [12] examined the flexural ability of externally fortified R.C. beams using side bonded CFRP sheets through epoxy adhesives. The increased flexural capacity of R.C. beams reinforced with a side-bonded system was compared to the found when using a conventional bottom-bonded reinforcement system. Specimens bonded with similar amounts of reinforcement were compared with higher flexural strength over the control beam of 62 to 92% for bottom bonded and 39.7 to 93.4% for side-bonded sections presented.
Several researchers have also conducted analytical studies, including Chahrour and Soudki [13]; Choi et al. [14]; Naji et al. [15]; Assi [16]. These researchers have attempted to analyse the behaviours of beams in order to develop a bonding system to improve load capacity. This paper focuses on the flexural behaviours of damaged R.C. box beams strengthened with CFRP sheet, and the flexural behaviours of partially bonded CFRP strengthened box beams are thus intensively investigated. The ultimate objective of the study was to achieve a balance between improvement of load-carrying capacity, the optimum configuration of CFRP sheets, and the corresponding reduction in deformability.

2. Specimen design
A list of investigated box beams is shown in table 1, while figure 1 shows the specimen geometry and reinforcement details. R.C. box beams with dimensions 2050x210x300 mm length, width, and depth, respectively, were created with 80x100 mm hollow cores. The tested box beams were designed according to ACI 318M-14 [17] to ensure flexural failure, and flexural retrofits were performed using CFRP sheets, as shown in Figure 2 to meet the needs of the experiment. The variables investigated included the configurations of CFRP sheets and damage ratios. The specimens in three groups were loaded with different damage ratios (45%, 60%, and 75%) of ultimate load. The specimens were then reloaded after repair with the carbon fibre sheets until failure.

| Group No. | Specimen symbols | Damage ratio | Strengthening details |
|-----------|------------------|--------------|-----------------------|
| Control Beam | SBC | Without damage | None |
| A | SBU1 | 45 % | Extend sheet under beams |
| | SBUB1 | 45 % | Extend sheet under beams & both side faces |
| | SBUM1 | 45 % | Extend sheet under beams & both sides faces to the middle |
| B | SBUB2 | 60 % | Extend sheet under beams |
| | SBUM2 | 60 % | Extend sheet under beams & both side faces |
| | SBUM2 | 60 % | Extend sheet under beams & both sides faces to the middle |
| C | SBU3 | 75 % | Extend sheet under beams |
| | SBUB3 | 75 % | Extend sheet under beams & both side faces |
| | SBUM3 | 75 % | Extend sheet under beams & both sides faces to the middle |

Table 1. Specimen list.
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Figure 1. Geometry and details of Box Beams.

Figure 2. Retrofit scheme using CFRP sheet.

3. Material properties

3.1. Concrete
Ordinary Portland Cement (Type I) of Iraqi origin was used in this study. The cement was tested as conforming to Iraqi I.Q.S NO.5 [18]. Fine aggregate from the Al-Ukhaidher region, available locally, was used, with a fineness modulus of 2.64, conforming to Iraqi I.Q.S NO.45 [19]. The coarse aggregate used was natural gravel with a maximum diameter of 12.5 mm on which characterisation tests were carried out as per Iraqi I.Q.S NO.45 [19]. Silica fume was used to improve the bond properties of the adhesive, and a polycarboxylate based high-range water reducing admixture (superplasticiser), was added to facilitate extreme water reduction and improve flowability while offering optimal cohesion and self-compacting behaviours. Several tests were carried out to assess the mechanical properties of the hardened SCC. The main tests (compressive strength, splitting tensile strength, and flexural strength) were completed per ASTM C 39M-17 [20], C 496M-11 [21], and C 78M-16 [22], respectively, with results as given in, Table 2.

Table 2. Properties of concrete.

| Properties         | Test result (MPa) |
|--------------------|-------------------|
| Compressive strength | 47.56             |
| Tensile strength    | 4.19              |
| Flexural strength   | 4.43              |

3.2. Steel reinforcement bars
Deformed steel bars with 10, 8, and 6 mm diameters as given Figure 1 and confirming to ASTM A615M-16 [23] and A496M-07 [24] standards, respectively were used. Deformed bars of 10 and 8 mm
diameter were used for the top and bottom longitudinal reinforcement, respectively. The stirrup reinforcement, with a diameter of 6 mm, was also deformed steel. The main data for the steel bars are listed in Table 3.

### Table 3. Properties of steel bar reinforcement.

| Bar size (mm) | Fy (MPa) | Fu (MPa) | Elongation (%) |
|---------------|----------|----------|----------------|
| 6             | 471.6    | 563.4    | 15.46          |
| 8             | 489.26   | 649.26   | 15.23          |
| 10            | 521.28   | 681.6    | 14.92          |

3.3. CFRP

SikaWrap-300 C was used for the external strengthening of the tested box beams. This offers a unidirectional fibre, so when the CFRP is loaded in tension, it shows no plastic behaviours (yield) prior to rupture. The mechanical properties of CFRP are shown in Table 4.

### Table 4. Mechanical properties of CFRP.

| Properties                      | SikaWrap-300 C |
|---------------------------------|----------------|
| Density (g/cm³)                 | 1.82           |
| Thickness (mm)                  | 0.167          |
| Tensile Strength (MPa)          | 3500           |
| Modulus of Elasticity (GPa)     | 225            |

3.4. Bonding materials

The recommended adhesive material for use with CFRP sheet is Sikadur-330; this come in two parts, resin and hardener, which are white and grey, respectively. The mix ratio used was A:B = 4:1, as recommended by the manufacturer. Table 5 displays the properties of the adhesive material.

### Table 5. Properties of bonding materials.

| Properties                        | Sikadur - 330 |
|-----------------------------------|---------------|
| Density (kg/L) at +23°C            | 1.30 + 0.1 (parts A+B mixed) |
| Tensile Strength (MPa) 7 days at +23°C | 30             |
| Modulus of Elasticity (GPa) 7 days at +23°C | Flexural : 3.8 / Tensile : 4.5 |
| Elongation at Break (%) 7 days at +23°C | 0.9           |

3.5. Polystyrene Block

To form the box beam, polystyrene blocks was used due to light weight and ease of configuration to the required dimensions. Polystyrene pieces were put at the cross-sections of specimens along the box beam to create a void in block concrete without adding resistance to the section as well as decreasing the box beams weight.

4. SCC mix design

Many trial mixes were conducted to meet the self-compacting specifications and to achieve the required compressive strength. The SCC mix was designed according to EFNARC 2005 [25]. Details of the adopted mix proportions (by weight) of the SCC used are shown in Table 6. This mix design gave excellent workability with no place segregation.
Table 6. Mix proportions.

| Volume of concrete | Cement | Fine Aggregate | Coarse Aggregate | Silica Fume | Super plasticizer | Water |
|--------------------|--------|----------------|-----------------|-------------|-------------------|-------|
| By Weight (kg/m³)  | 400    | 800            | 750             | 40          | 5                 | 140   |
| By Volume          | 1      | 2              | 1.875           | 0.1         | 0.0125            | 0.35  |

5. Test set-up
All specimens were loaded with a testing machine with a maximum capacity of 2,000 KN. The beam was held horizontally under two concentrated loads with a hinge at a distance of 7.5 cm from the end support while the machine applied sustained monotonic loading at the supports of the beam, as shown in Figure 3.
Except for the control box beam, all the other box beams were checked in groups (before retrofitting) with different damage ratios from the ultimate load, as mentioned in table 1 for the control beams. Each ratio of damage represents a certain service load in reality, as shown in Figure 4. Loading was then applied at regular increments, and the load-deflection behaviours recorded for each box beam.

6. Results and Discussion
6.1. Test results
The results before and after retrofitting of damage loads, cracking loads, ultimate loads, and mid-span deflection at first cracking, and ultimate deflection are shown in Table 7.

Figure 3. Test set-up.

Figure 4. Damaged samples with different damage ratios.
Table 7. Results of box beams.

| Specimen symbols | Damage load | Before Retrofitting | After Retrofitting | $\frac{P_{cr}}{P_u}$ (%) |
|------------------|-------------|---------------------|---------------------|--------------------------|
|                  |             | load at First crack | deflection at First crack | Ultimate load | Ultimate deflection |
|                  |             | $P_{cr}$ (KN)       | (mm)                | $P_u$ (KN)      | (mm)               |
| SBC              | without     | 25.41               | 2.48                | 62.31          | 22.02              | 40.78              |
| SBU1             | 28.04       | 27.68               | 2.78                | 93.53          | 11.73              | 29.6               |
| SBUB1            | 28.04       | 28.24               | 2.43                | 133.27         | 15.46              | 21.19              |
| SBUM1            | 28.04       | 24.84               | 2.17                | 118.51         | 14.94              | 20.96              |
| SBU2             | 37.38       | 25.97               | 2.87                | 94.81          | 12.69              | 27.39              |
| SBUB2            | 37.38       | 26.54               | 2.26                | 131.57         | 14.42              | 20.17              |
| SBUM2            | 37.38       | 27.68               | 3.04                | 100.34         | 12.25              | 27.59              |
| SBU3             | 46.73       | 25.41               | 2.09                | 88.99          | 11.64              | 28.55              |
| SBUB3            | 46.73       | 26.54               | 2.35                | 108.86         | 11.91              | 24.38              |
| SBUM3            | 46.73       | 26.56               | 2.17                | 98.96          | 12.61              | 26.84              |

6.2. Crack pattern and crack observations
The failure mode of all control box beams was flexural. The box beams retrofitted with CFRP failed due to debonding or tearing of CFRP or crushing of concrete, as in SBU3, where crushing of concrete occurred in addition to CFRP debonding. All box beams showed the same pattern of failure, with failure modes as shown in Figure 5.

Figure 5. Crack patterns of specimens at ultimate load.
6.3. Ultimate load capacity
External strengthening of SCC damaged box beams with CFRP sheets showed improvements in ultimate load capacity of 42 to 114% as compared with the capacity of the control box beam without strengthening, as shown in Figure 6. The change in the strengthening shape of CFRP sheets, and the damage ratios lead to a change in the ultimate load in most cases. The results also showed that side strengthening (Extending the sheet under beams with both sides facing) provided an effective tool for increasing the ultimate load capacity, with an increase of over 28% on average as compared to those seen with other methods, as well as a reduction in crack widths.

![Ultimate load for all groups](image)

**Figure 6.** Ultimate load for all groups

6.4. Load-Deflection behavior
Load-deflection curves for SCC box beams strengthened with CFRP indicate the development of flexural cracks, which extended over the central bending span. The control and strengthening box beams Load-Deflection curves are shown in Figures 7, 8, and 9. Cracking loads and ultimate loads were applied to all box beams, and the first crack was formed at about 39.9 to 45.3% of the ultimate load for all box beams. Adding CFRP sheets affected the behaviours of strengthened box beams as compared with the control box beams by increasing the ultimate strength and reducing the ultimate mid-span deflection ratio by over 40%.
Some samples with the same retrofit amount with different damage ratios had greater strength than others such that the damage ratio appears to have an effect on the ultimate load of not less than 18%.
Figure 7. Curve of load-deflection for Group A.

Figure 8. Curve of load-deflection for Group B.
7. Conclusions
This paper assesses the strengthening of damaged reinforced concrete box beams by gluing carbon fibre sheets to the outside. The primary aim was to study of the flexural strength of pre-cracked R.C. box beams with different damage ratios and to compare the ultimate loads of control beams strengthened externally with CFRP in different configurations to determine the best way to enhance the flexural strength of damaged box beams. Ten R.C. box beams were thus tested under monotonic two-line loads. The following conclusions emerge from the outcome of this investigation:

1. The reduction in deflection for SCC box beams changes depending on the quantities and position of CFRP sheets used to strengthen such beams.
2. The results demonstrate that the use of CFRP system for strengthening improves the flexural efficiency of R.C. box beams SCC. The contribution of repair by gluing on CFRP materials is a considerable improvement in ultimate load capacity of 42 to 114% as compared with reference specimens without strengthening, as well as a reduction in the ultimate mid-span deflection ratio by over 40% at ultimate load.
3. All box beams were loaded to ultimate loads and cracking loads; first crack formation was at around 39.9 to 45.3% of the ultimate load for box beams.
4. The results showed that the damage ratio has an effect on the ultimate load of not less than 18%.
5. All strengthened box beams failed due to fabric rupture regardless of strengthening methods.
6. Change in the strengthening shape of CFRP sheets and the damage ratios between them leads to a change in the ultimate load in most cases. Side strengthening (extending sheet under beams with both sides facing) provides an effective tool for increasing the ultimate load capacity by over 28% on average, as well as reducing crack widths.
7. Adding composite fibre sheets using External Bonding (EB) technology offers a convenient and effective strengthening method for the rehabilitation of damaged structures.
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