Visual Abstract

The behavior of reinforced lightweight concrete beams with initial cracks

Mustafa Q. Hasan, Abdulkhalik J. Abdulridha
Department of Civil Engineering, College of Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq
mustafa88qusay@gmail.com
Abdulkhalik.J.AbdulRidha@nahrainuniv.edu.iq, https://orcid.org/0000-0001-6403-2325

ABSTRACT. This research examines the performance of reinforced lightweight concrete beams subjected to several degrees of damage (50%, 60%, 70%, and 100%). It can use a sheet made of Carbon Fiber Reinforced Polymer (CFRP) to reinforce. The Full U-wrapping rehabilitation method was tested in the presented experimental program. In this method, CFRP sheets are attached to the bottom only and the side and bottom of the beam section. Experiments proved that the service load (Ps) increases by 7.06 % from a damage level of 50 % to 70 %, rises by 1.21 % from a damage level of 60 % to 70 %, and falls by 3.07 % from a damage level of 100 %. The result also rose for the fortified sample by 11.99%. Increases of 42.67 %, 33.07 %, and 23.73 % in the stiffness ratio (k) were observed at damage intensities of 50, 60, and 70 %, respectively. Damage at lower severity levels is increasing at a faster rate. The ductility of the restored LWC beams is more excellent than the control, as with the stiffness. Damage levels of 50%, 60%, and 70% saw increased ductility of 35.60, 34.92, and 34.69 %, respectively.

KEYWORDS. Lightweight concrete, Rehabilitation, Carbon fiber, U-wrapping, CFRP.

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INTRODUCTION

There is a growing interest in using fiber-reinforced polymer FRP technology to update RC construction. FRP has been widely used for repairing and replacing worn-out and broken structures. Changes in CFRP thickness have a significant effect on the ultimate load-bearing capability. Longitudinal soffit-bonded CFRP strips are used to reinforce shear-weak RC beams so that they are better able to bear lateral service loads, as opposed to the more common transversely aligned or wrapped CFRP strips, used in multi-girder bridge decks. [1-4]. Using fewer resources in construction yields savings in both energy and money [5-7]. LWA's output includes a material known as Lightweight Aggregate Concrete (LWAC).

The compressive strength of LWAC (concrete with a weight per cubic meter of less than 1800 kilograms) is greater than 18 MPa [8-10]. Lightweight Aggregate Concrete (LWAC) is most often used to increase the insulating properties of a structure, particularly in terms of heat and sound. Traditional aggregates are replaced by lightweight aggregates (LWA), which may be made from natural materials like pumice, diatomite, and volcanic ash or manufactured materials like perlite, extended schist, clay, slate, and sintered powdered fuel ash (PFA). Lightweight aggregate concrete (LWAC) replaces natural aggregates with manufactured rocks that are less dense but still strong [11-15]. This type of concrete has scientific and commercial benefits, and the environment may also benefit from using LWAC. The mechanical properties of LWAC are determined by mix design (water-to-cement ratio, quality, and aggregates' characteristics), the preformed foam's quality, and the type of foaming agent [16-19]. FRP can be added to the mix to make concrete or bricks more durable. A significant concern when dealing with FRP [20] is that the reinforcement can separate from the attached material. Changes in body damage substantially affect how smoothing works [21], but only until damage at the interface exceeds that at the body.

For many reinforced concrete building systems, reducing the dead load is essential for relieving stress on the supporting structures and cutting costs. Insulation from heat and sound is a common requirement for many newer structures [22]. The relatively high water-to-cement (W/C) ratios were once the norm in the concrete industry. The hybrid variety's resilience to both drought and pests is exceptional. Nonetheless, there are usual difficulties, as shown by shrinking at cracking [23], despite these benefits. While chemical shrinkage occurs in both high and low W/C mixes, low W/C mixes are more prone to self-drying out because of holes and capillary pressure, which produces fractures [23-25]. LWC (lightweight concrete) might solve many of these problems. If the weight placed on an RC beam is more significant than it can support, it will crack. Although unlikely, this can occur, especially if the building's framework is experiencing significant stress [26]. This study looks at the feasibility of employing FRP designs to secure LWC beams. Light Weight Aggregate (LWA) has a reduced density of mass compared to Normal Weight Aggregate (NWA) [27]. Adopting LWA for internal hardening in RC applications may increase the service life of the entire structure by reducing early-age stresses and shrinkage. Researchers have shown that introducing LWA increases moisture, increases mechanical strength across a broader range, and reduces heat conductivity [28]. After drilling, the pressure inside the capillary holes will drop because the cement paste will hydrate and dry out independently, allowing water from the LWA's perforations to soak into the cement.

It is essential to supply enough water inside the LWA—paste system and guarantee that it is distributed uniformly for proper paste integration. The concept's central defining feature controls water flow inside the grid: the distance between LWA particles. According to the statistics reported in this paper, increasing the LWA substitution ratio might dramatically improve water distribution [22]. Lightweight Expanded Clay Aggregate (LECA) is a kind of LWA produced by heating clay to 1200 C in a rotating kiln. Due to the decompression of the gases upon boiling, thousands of bubbles make up the bulk of this mixture. As a result of these gases, clay tends to expand, taking on a honeycomb pattern [29]. Most rotating kilns have a round form because of the way they produce heat. This chemical will be used as LWA in the synthesis of LWC in this experimental research. FRP use in this capacity has become prominent in recent years. The superiority of some materials over more common ones like steel makes this abundantly clear. Utilizing three primary types of FRPs for RC beam strengthening and repair are studied. CFRP is an early leader in this field. The second variety is a composite reinforced with aramid and glass fibers. CFRP is the best material for strengthening and repairing RC beams.

When components of a building are upgraded either before or after they begin to fail, this process is known as a retrofit. Restoration, however, covers how a damaged building can be fixed. Recent articles published in peer-reviewed journals in this discipline have dabbled in various formats and mediums. Pilot programs are frequently used to test these methods. People are always making an effort in the pursuit of better results. An essential part of recovery is pinpointing what went wrong. This factor may come into play while deciding what to do next. For these reasons, many scholars maintain that this topic still merits study. Due to the minimal likelihood of repeating border conditions, this is a serious concern. As a result, the strategy taken may be affected by factors such as technology, economics, and even society [30-32].

OUTLINE OF THE EXPERIMENTAL SECTION

The research investigates what happens to beams made of reinforced lightweight concrete when they sustain 50%, 60%, 70%, or 100% damage. Use the CFRP sheet to strengthen. Five reinforced lightweight concrete beams span 1600mm center to center and 1800mm total length. The dimensions of the beam section are a total height of 300mm and the width of 200mm. The 2 Ø 8mm top reinforcement and 3 Ø 12mm bottom steel bars were used as primary reinforcement. Additionally, Ø 10 mm @ 120mm were used as stirrups, illustrated in Fig. 1. Tab. 1 shows the beam specimen descriptions.

The first digit of the specimen number indicates whether the sample was strengthened (S) or repaired (R). The second number (F), means that the Full wrapping method is used over the whole section height. The severity of the damage (in terms of ultimate load) is indicated by the last digit. Tabs. 2 and 3 show the chemical and physical parameters of the regular Portland cement utilized in this experiment, and they conform to the Iraqi standard specification (I.Q.S No.5-2019). We've been using natural sand with a maximum particle size of 4.75 millimeters. As shown in Tab. 4, it satisfies the grading requirements of the Iraqi standard specification (I.Q.S No.45-1984). Tab. 5 shows that the maximum diameter of the lightweight coarse aggregate LECA employed in this investigation is 12 mm. This material replaced the coarse aggregate in the LWC. Iraqi standards (I.Q.S. No.45-1984) were used to conduct the necessary testing on this sand.

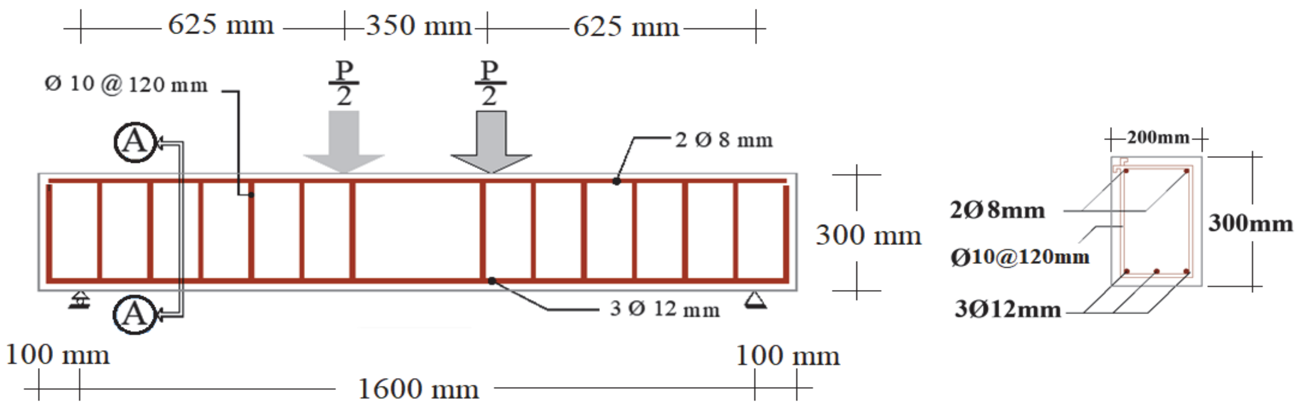

Figure 1: Specimen dimensions of the present study Sec. (A-A).

Specimen designation	Description
Control	Referential specimen without CFRP
SF-100	Strengthened beam with full wrapping CFRP sheets.
RF-50	Repaired beam with full U-wrapping CFRP sheets and subjected to 50% of damage.
RF-60	Repaired beam with full U-wrapping CFRP sheets and subjected to 60% of damage.
RF-70	Repaired beam with full U-wrapping CFRP sheets and subjected to 70% of damage.

Table 1: Beam specimens' descriptions.

Oxide	Percentage by weight%	Limit of IQS No. 5/ 2019
CaO	60.37	-
SiO2	20.74	-
Al2O3	5.78	-
Fe2O3	3.48	-
MgO	1.91	< 5.0%
SO3	1.85	≤ 2.8% for C3A ≥ 3.5%
Loss on Ignition (L.O.I)	2.44	< 4.0%
Lime Saturation Factor (L.S.F)	0.92	0.66 - 1.02
Insoluble residue (I.R)	0.19	< 1.5 %
Main compound (Bouge equation) % by weight of cement	-	Limit of IQS No. 5/ 2019
C3S	41.7	-
C2S	27.4	-
C3A	10.2	-
C4AF	9.9	-

Table 2: Chemical analysis of cement.

Physical properties	Test result	Limit of IQS No. 5/ 2019
Fineness, Blaine, gm/cm^2	319	>230
Setting Time: Initial, min	95	≥45 min
Setting Time: Final, min	410	≤10hrs

Table 3: Physical analysis of cement.

Diameter of Sieve (mm)	Percent of Passing %
10	100
4.75	99
2.36	96
1.18	90
0.60	84
0.300	50
0.150	12

Table 4: Sand sieve analyses.

Diameter of Sieve (mm)	Percent of Passing %
75	100
63	100
37.5	100
20	97
14	38
10	30
5	0
2.36	0

Table 5: LECA sieve analyses.

The high-range water-reducing additive PC600 (superplasticizer) was used. It has a specific gravity of 1.22, and its properties, meet the requirements of both BS 5075 and ASTM C494. Mixing Water Concrete was mixed and hardened using Baghdad's tap water. This study kept this water clear and pure as much as possible. Reinforcing deformed bars used throughout the present study are 8mm and 10mm, and 12mm in diameter. The reinforcing steel testing results of such bars are listed in Tab. 6. Such tests, are done according to American Testing Standard Measurements (ASTM) A615. These tests were done at the University of Al-Nahrain concrete laboratory. CFRP SikaWrap-300 C unidirectional, woven, carbon-fiber fabrics have been used to reinforce the beams externally. Tab. 7 shows the CFRP laminates' mechanical properties. The bonding material for the appropriate adhesive material for CFRP sheets is Sikadur-330. There's a white paste (the Resin) and a grey paste (the Hardener) that make up the two halves. According to the manufacturer, the ideal mix ratio is (4:1). Tab. 8 shows some of the characteristics of the used adhesive material.

Nominal diameter mm	Yield stress MPa	Yield strain	Ultimate strength MPa	Ultimate strain	Elongation %
8	489.26	0.00244	629.26	0.00282	15.46
10	501.93	0.00253	635.09	0.00301	13.58
12	505.12	0.00268	646.96	0.00357	12.77

Table 6: Tension tests results for steel bars within this study.

Properties	SikaWrap-300 C
Density (g/cm^3)	1.8
Thickness (mm)	0.17
Tensile Strength (MPa)	3900
Modulus of Elasticity (GPa)	230
width (mm)	300

Table 7: The technical properties of CFRP.

Properties	SikaWrap-300 C
Density (kg/L)	1.30 (mixed component A+B mixed) (+23°C)
Modulus of Elasticity in flexure (GPa)	3.8 (7 days, +23°C)
Modulus of Elasticity in tension (GPa)	4.8 (7 days, +23°C)
Tensile Strength (MPa)	30 (7 days, +23°C)
Elongation at Break (%)	0.88 (7 days at +23°C)
Mixing ratio	4 : 1

Table 8: Properties of the used bonding materials.

Concrete mix design

The mix-design of the LWC that existed in this study is presented in Tab. (9). This mix reflected 1700 kg/m³ of density. However, the required compression strength and slump were achieved after several trial mixtures.

Material	Cement (kg/m³)	Sand (kg/m³)	LECA (kg/m³)	Water (kg/m³)	Admixture (Liter/m³)
Quantity	480	600	500	144	5

Table 9: Concrete mixture proportions.

The rehabilitation technique

The rehabilitation technique was implemented and examined in the presented experimental program called Full U-wrapping. In this technique, CFRP sheets are installed to cover the section bottom and the full-height of its sides, as shown in Fig. 2. This technique consists of four specimens; the first is RF-50, an LWC beam that was repaired with full-height U-wrapping CFRP sheets and subjected to 50% of damage, as shown in Fig. 3. The second is RF-60, an LWC beam that was repaired with full-height U-wrapping CFRP sheets and subjected to 60% of damage, as shown in Fig. 4. The third is RF-70, an LWC beam that was repaired with full-height U-wrapping CFRP sheets and subjected to 70% of damage, as shown in Fig. 5. The last specimen is SF-100, a strengthened LWC beam by full-height U-wrapping CFRP sheets, as shown in Fig. 6. The structural behavior of the specimen is compared with a control specimen (Referential specimen without CFRP).

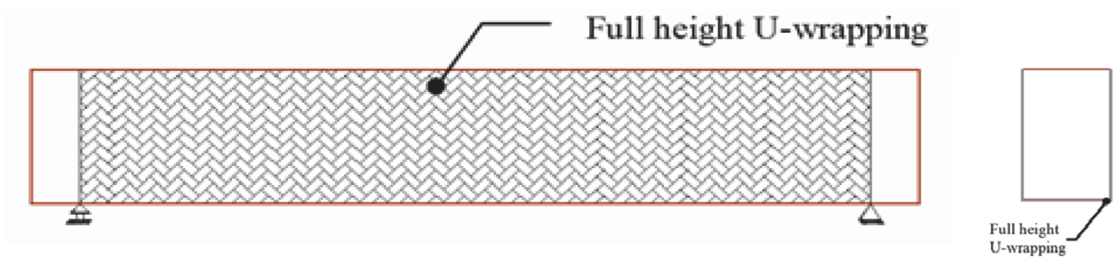

Figure 2: Full-height U-wrapping.

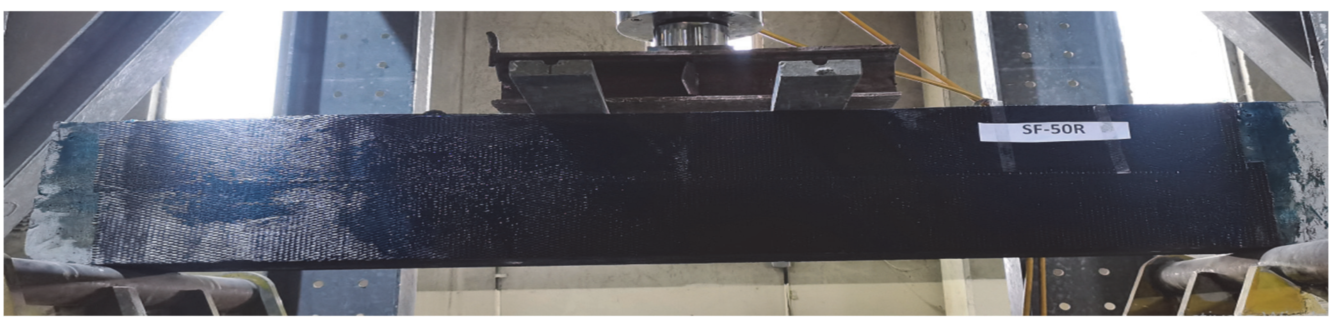

Figure 3: Full-height U-wrapping CFRP sheets and subjected to 50% of the damage.

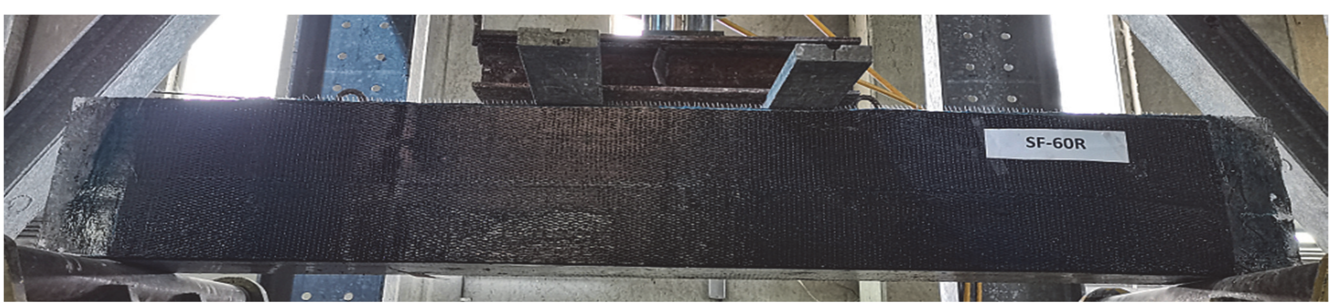

Figure 4: Full-height U-wrapping CFRP sheets and subjected to 60% of the damage.

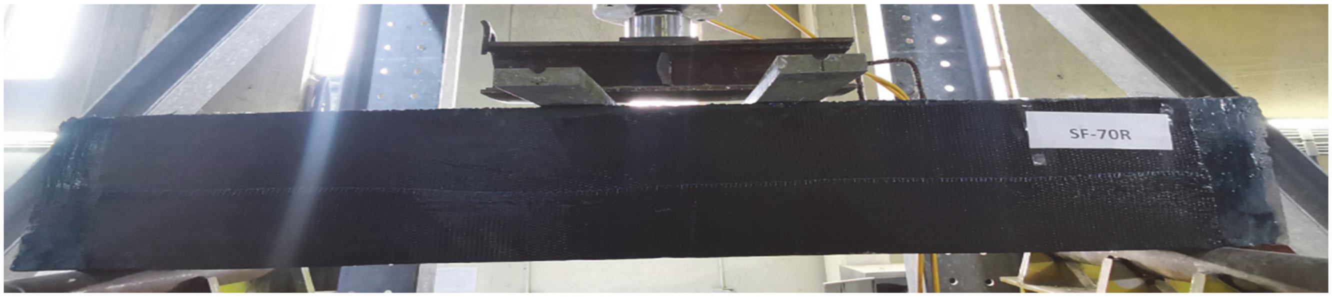

Figure 5: Full-height U-wrapping CFRP sheets and subjected to 70% of the damage.

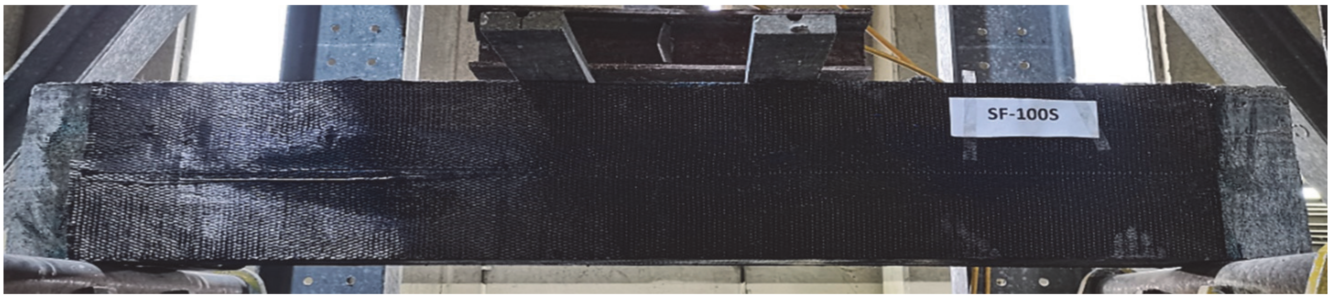

Figure 6: Full-height U-wrapping CFRP sheets and subjected to 100% of the damage.

Rehabilitation procedure

First, as shown in Fig. 7, the per-failed specimens were mechanically ground to a satisfactory smoothness using appropriate grinding commercial sheets. After that, an air compressor was used to clean the beams, preventing dust from settling on the specimens. To produce the adhesive material for the CFRP installation, KUT BOND Epoxy was mixed using a laboratory spatula. Figs. 8 and 9 demonstrate how these sheets were placed and established using an appropriate roller to prevent trapped air.

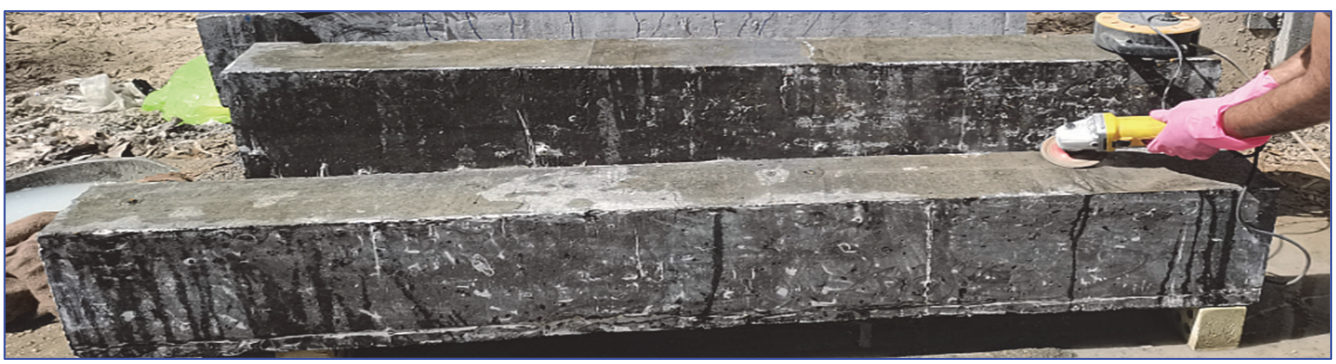

Figure 7: Mechanical Grinding.

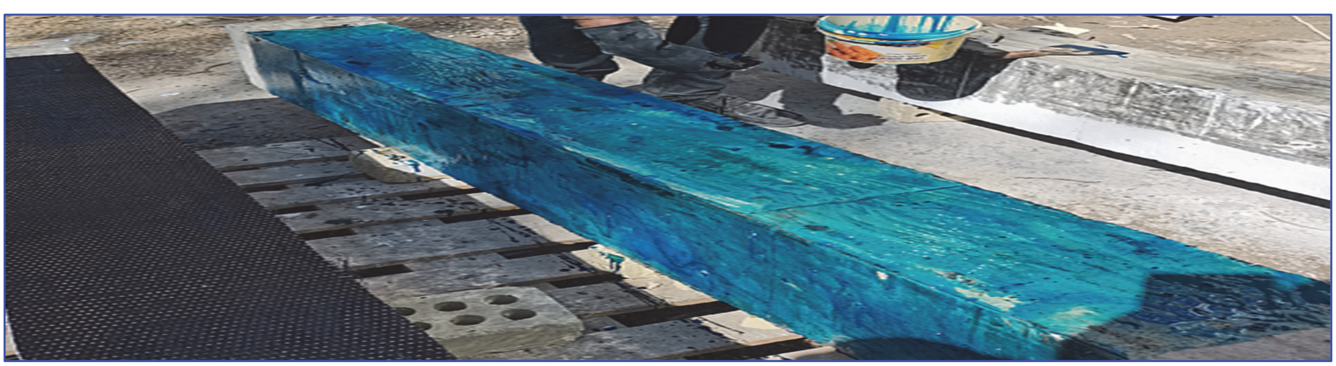

Figure 8: KUT BOND Epoxy.

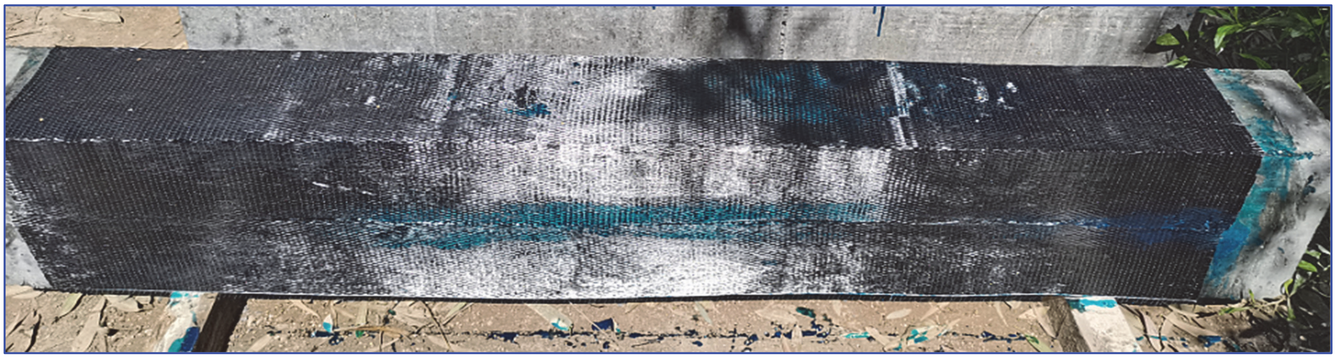

Figure 9: Installing CFRP.

RESULTS AND DISCUSSION

Loading Capacity

TAb. 10 and Fig. 10 shows the size effect degree of damage to the Ps and Pu of LWC beams rehabilitated by full-height U-wrapping CFRP sheets. Changing the degree of damage from 50% to 70% increased the Ps by 7.06% and 1.21% for 50% and 60%, respectively, while it decreased by 3.07 for 100%. In addition, such value increased the strengthened specimen by 11.99%. Service load Ps levels decreased as damage severity increased for LWC beams rehabilitated with full-height U-wrapped CFRP sheets. Using such a technique recovers this value for 50% and 60%, but when this degree is extended to 70%, Ps is lower than the control reading. This can be attributed to the consequent considerable mechanical performance of the CFRP – Epoxy composite that can compensate for the loss in structural rigidity-for Pu, increasing the degree of damage from 50% to 70% decrease this value. However, implementing full-height U-wrapping CFRP sheets can recover this value increasingly (as damage decreased) by 11.47%, 6.31%, and 0.57% for 50%, 60%, and 70% degrees of damage, respectively. Ps value for the strengthened specimen is more than the referential reading by 14.81% due to the consequent gain in structural rigidity. For, Pcr levels reported 40.08 kN and 78.56 kN, which corresponds to an excellency of 96% for the strengthened beam. Further research is needed to investigate the degree of the relation between the degree of damage and the relevant Pcr, Ps, and Pu.

Beam Specimen	Service load Ps (kN)	Increasing in service load Ps %	Ultimate load Pu (kN)	Increasing in ultimate load Pu %
Control	168.47	-	197.99	-
RF - 50	180.34	7.06	220.70	11.47
RF - 60	170.51	1.21	210.48	6.31
RF - 70	163.30	-3.07	199.12	0.57
SF - 100	188.67	11.99	227.32	14.81

Table 10: The Ps and Pu for LWC beams rehabilitated by full-height U-wrapping CFRP sheets.

DEFLECTION

TAb. 11 and Fig. 11 demonstrate the extent of damage remedied by full-height U-wrapping CFRP sheets on LWC beams. There is a drop of 24.97 %, 23.95 %, and 21.66 %, respectively, when the damage is increased from 50 to 60 to 70 %, compared to the control. The same three groups had decreases of 6.98%, 8.75%, and 9.35%, respectively. Good mechanical characteristics of CFRP- Epoxy composite (stiffness) in the early response phases led to a reduction in all existing damage degrees in this investigation. Due to the different degrees of crushing the concrete pieces before restoration, the levels also reduced as the degree of damage proceeded. The reinforced beam has a lower weight (31.47% lower) and a higher strength (3.11%) than the control beam (no early crushing in concrete cracking before attaching CFRP sheets). Load-deflection plots for the Control, RF-50, RF-60, RF-70, and SF-100 configurations, are shown in Fig. 12. Phase I (Elastic) of the control specimen lasts until the first cracking limit is reached. By its conclusion, the fissures will be visible.

Phase II (Phase II) occurs after the initial cracking load when the cracks increase in number and breadth. This continues till the Ps. Once this threshold was passed, the last step (step III) created wider-cracks. Phase I and II inflection points are also easily identifiable, as is Ps, and this holds over a wide range of damage intensities. Phase III is extended for the reinforced specimen in comparison to the control.

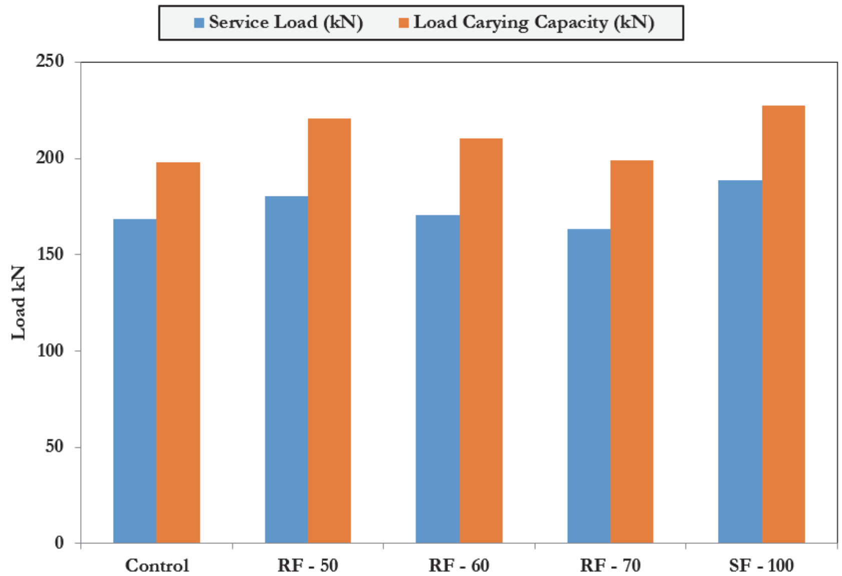

Figure 10: The Ps and Pu for LWC beams rehabilitated by full-height U-wrapping CFRP sheets.

Beam Specimen	Service displacement P_s (mm)	Decreasing in Service displacement Δ_s %	Ultimate displacement Δ_m (mm)	Changing in ultimate displacement Δ_m %
Control	25.39	-	38.27	-
SF - 100	17.4	-31.47	39.46	3.11
RF - 50	19.05	-24.97	35.6	-6.98
RF - 60	19.31	-23.95	34.92	-8.75
RF - 70	19.89	-21.66	34.69	-9.35

Table 11: The Δ_s and Δ_m for LWC beams rehabilitated by full-height U-wrapping CFRP sheets.

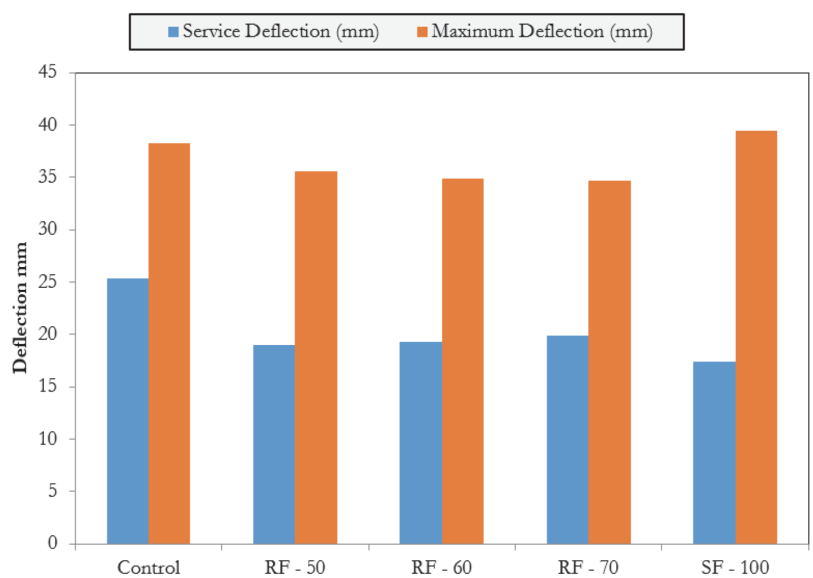

Figure 11: The Δ_s and Δ_m for LWC beams rehabilitated.

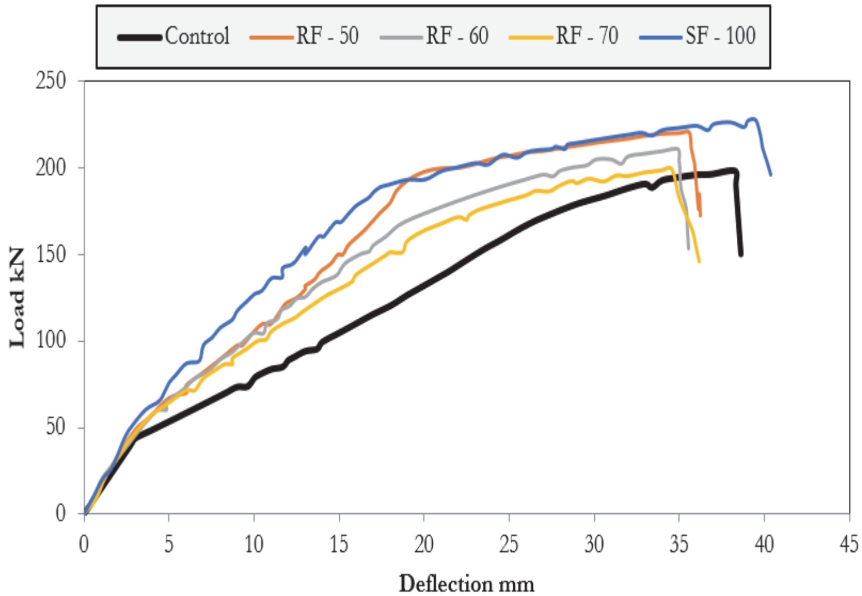

Figure 12: Load deflection response for LWC beams rehabilitated by full-height U-wrapping CFRP sheets.

FAILURE MODE

Fig. 13 shows the failure mode visual observation of the control specimen. The normal tension failure mode (flexure failure) was observed for the control specimen. In addition, crack propagation was always expected, and no cracks had reached the extreme compression fiber. Fig. 14 shows the failure mode of the beam specimen (SF-100). It is clear that the cracks propagated increasingly as the degree of damage progressed the RF-50, RF-60, and RF-70, as shown in Fig. 15. After rehabilitation, the mode of failure was transformed to crushing failure for all the degrees of damage proposed. This form of failure was also observed in the strengthened specimen.

Figure 13: The mode of failure for the beam specimen (Control).

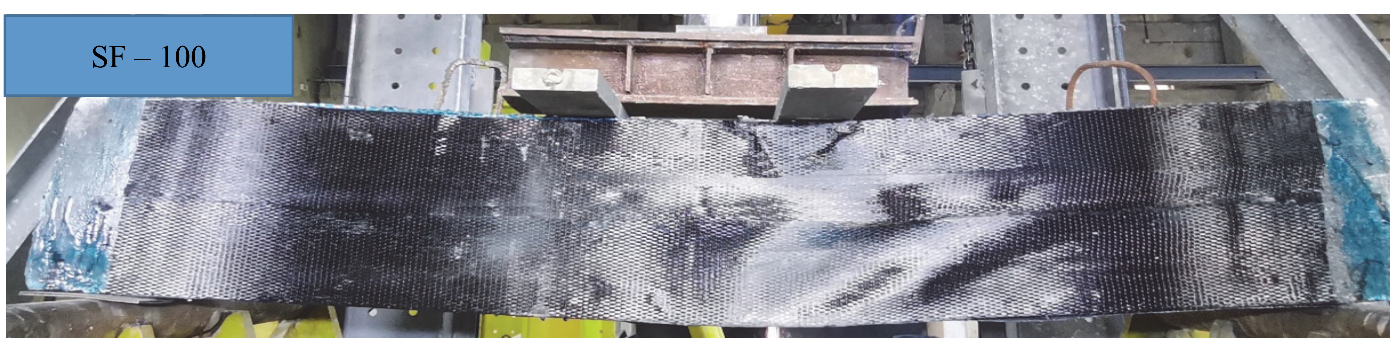

Figure 14: The mode of failure beam specimen (SF – 100).

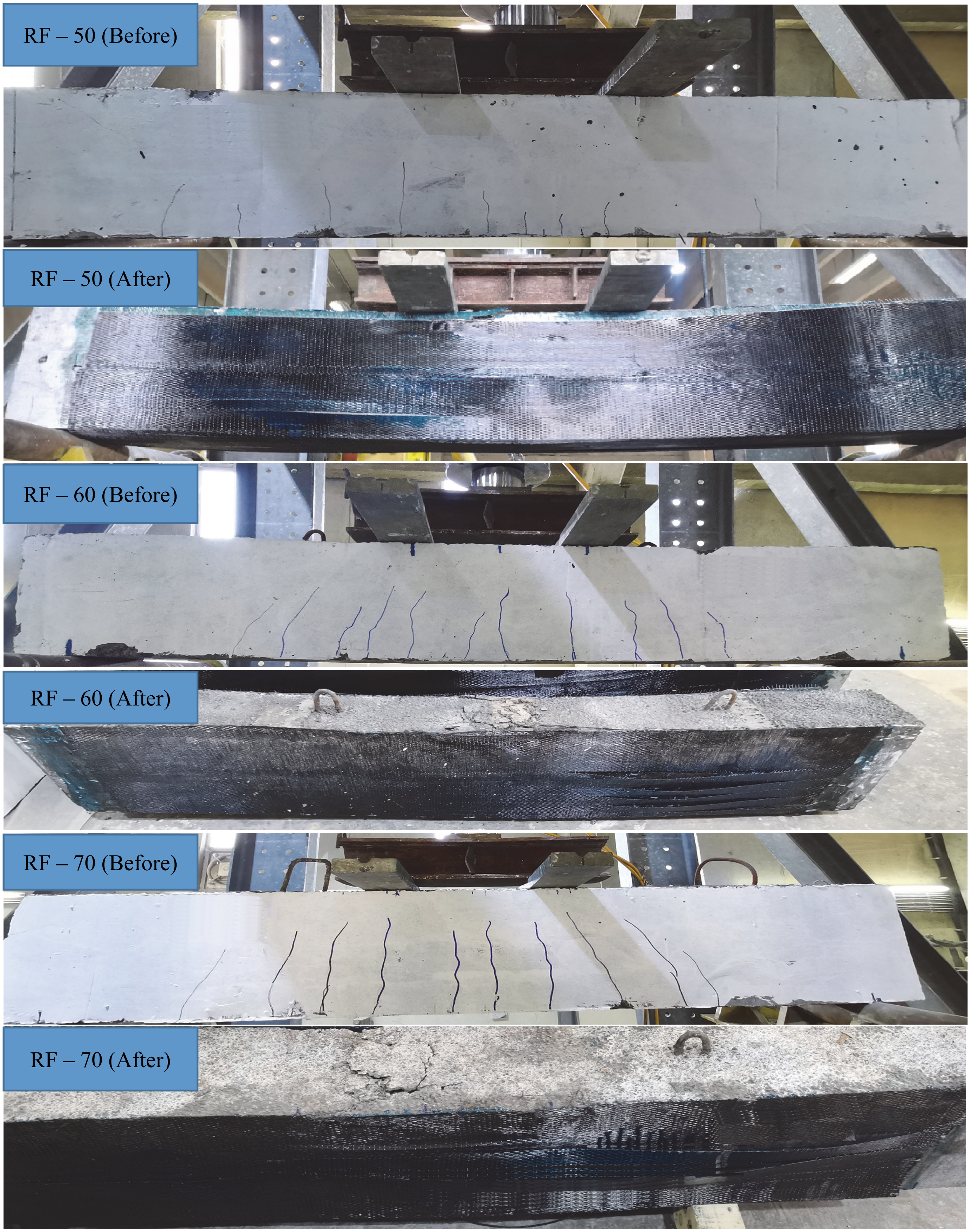

Figure 15: The mode of failure for the full-height U-wrapping CFRP sheets rehabilitation technique

STIFFNESS RATIO (K)

Throughout the current study, the stiffness behavior of LWC rehabilitated beams is characterized by the stiffness ratio (k) as shown in Eq. 1:

$$k = \frac{P_s}{\Delta_s} \quad (1)$$

where k= Stiffness Ratio (kN/mm), P_s = Service load (kN), and Δ_s = Service deflection (mm). Tab. 12 and Fig. 16 show the degree of damage effect to k of LWC beams rehabilitated by full-height U-wrapping CFRP sheets. Compared to the control specimen, the stiffness of the rehabilitated LWC beams by full-height U-wrapping CFRP sheets is more than the referential reading. For degrees of damage of 50%, 60%, and 70%, k levels were increased by 42.67%, 33.07%, and 23.73%, respectively. The rate of increase is more in the low levels of degree of damage. This can be attributed to the high levels of Ps and low and the consequent levels due to the reason discussed in the previous section. For the strengthened beam, the stiffness is also more than the control (63.42%) and the rehabilitated beams. Another effort should be devoted to exploring the degree of relation between the degree of damage and the related k.

Beam specimen	Service displacement Δ_s (mm)	Service load Ps (kN)	Stiffness ratio (k) kN/mm	Increasing in stiffness ratio k %
Control	25.39	168.47	6.64	-
RF - 50	19.05	180.34	9.47	42.67
RF - 60	19.31	170.51	8.83	33.07
RF - 70	19.89	163.30	8.21	23.73
SF - 100	17.4	188.67	10.84	63.42

Table 12: The stiffness ratio (k) for LWC control and rehabilitated beams by full-height U-wrapping CFRP sheets.

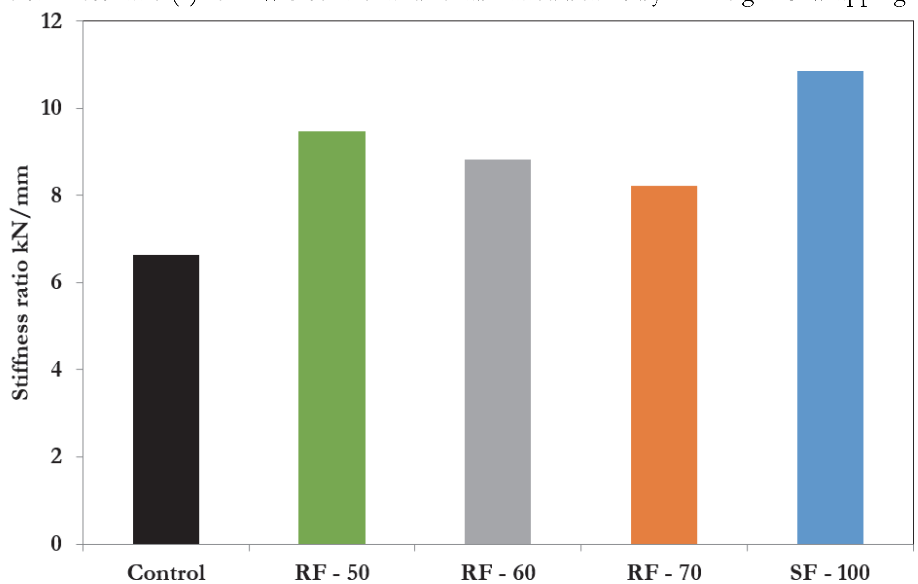

Figure 16: The stiffness ratio (k) for LWC control and rehabilitated beams by full-height U-wrapping CFRP sheets.

DUCTILITY FACTOR (D)

During this study, the ductility behavior of LWC rehabilitated beams is represented by the stiffness ratio (d) as shown in Eq. 2:

$$d = \frac{\Delta_m}{\Delta_s} \quad (2)$$

where d= Ductility factor, Δ_m = Service load (kN) and Δ_s = Service deflection (mm). Tab. 13 and Fig. 17 show the degrees of damage effect to d of LWC beams rehabilitated by full-height U-wrapping CFRP sheets. As in the stiffness, the ductility of the rehabilitated LWC beams by full-height U-wrapping CFRP sheets is more than the control. For degrees of damage of 50%, 60% and 70%, d levels were increased by 35.60%, 34.92% and 34.69%, respectively. As in the stiffness behavior, the rate of d increase is more when the degree of damage was low due to the Δ_s and Δ_m levels. The strengthened specimen has a high level compared to the control (50.46%). Again, this happened due to the inherent low level of Δ_s and high level of Δ_m. More research on this topic is needed to be undertaken about correlating d to the degree of damage for any CFRP rehabilitation technique.

Beam specimen	Service Deflection (mm)	Maximum Deflection (mm)	Ductility Factor (d)	Increasing in Ductility Factor d %
Control	25.39	38.27	1.51	-
RF - 50	19.05	35.60	1.87	23.98
RF - 60	19.31	34.92	1.81	19.98
RF - 70	19.89	34.69	1.75	15.70
SF - 100	17.4	39.46	2.27	50.46

Table 13: The ductility factor (d) for LWC beams rehabilitated by full-height U-wrapping CFRP sheets.

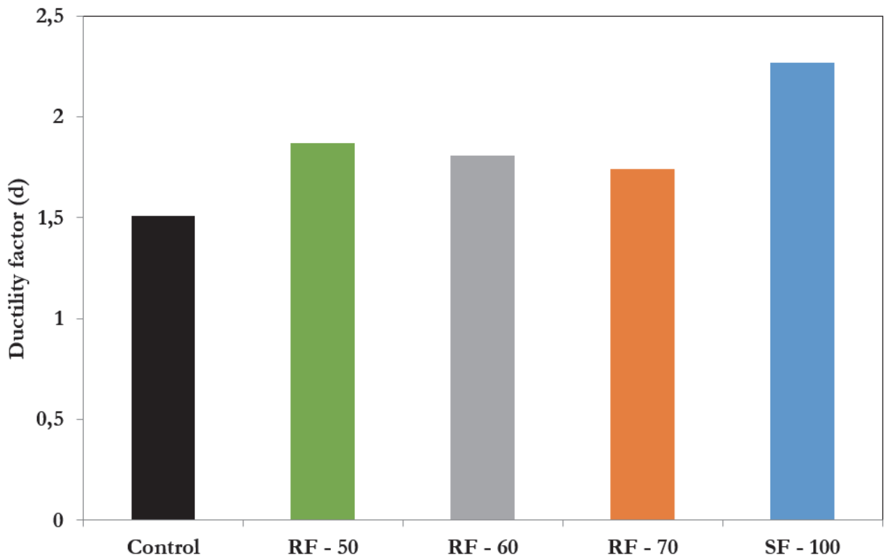

Figure 17: The ductility factor (d) for LWC control beams rehabilitated by full-height U-wrapping CFRP sheets.

Conclusion

The following conclusions can be drawn:

1. Using full-height U-CFRP wrapping can recover the inherent structural behavior characteristics of LWC beams.
2. Increasing the degree of damage in the LWC beams decreases the performance characterization parameter such as service load and load carrying capacity for the proposed techniques.
3. Increasing the degree of damage decreases the relevant ductility and stiffness of LWC beams for all the proposed techniques when the proposed technique is used for strengthening, the flexural performance was increased.

4. The service load (Ps) increased by 7.06 % at a damage level of 50 % versus 60 % and 1.2 % at 70 %, while it decreased by 3.07 % at a damage level of 100 %. The value also contributed to an 11.99% boost in strength in the improved specimen.
5. Service deflection decreased across the board due to the stiffness of the CFRP-Epoxy composite in the early stages of response, with increases in stiffness ratio (k) of 42.67 %, 33.07 %, and 23.7 for damage levels of 50 %, 60 %, and 70 %, respectively.
6. The rate of escalation is the greatest for moderate and minor damage levels.
7. Rehabilitated LWC beams with complete U-wrapped CFRP sheets have superior ductility than the originals, just as they do in stiffness.
8. The levels of deflection increased by 35.60 %, 34.92 %, and 34.69% for damage levels of 50 %, 60 %, and 70 %, respectively.
9. Restoring the original structural behavior features of LWC beams is possible with full U CFRP wrapping.
10. The service load and carrying capacity of the LWC beams diminish with increasing deterioration.
11. The ductility and stiffness of LWC beams are affected by the severity of the damage they have sustained.

References

[1] Harba, I., Abdulridha, A. and ALShaar, A. (2023). Numerical analysis of reinforced concrete circular columns strengthening with CFRP under concentric and eccentric loadings, Frattura ed Integrità Strutturale, 63, pp. 190- 205. DOI: 10.3221/IGF-ESIS.63.16.

[2] Madqour, M., Hassan, H. and Fawzy, K. (2022). Finite element modeling of flexural behavior of reinforced concrete beams externally strengthened with CFRP sheets, Frattura ed Integrità Strutturale, 59, pp. 62-77; DOI: 10.3221/IGF-ESIS.59.0.

[3] Risan, H., Harba, I. and Abdulridha, A. (2017). Numerical analysis of RC wall with opening strengthened by CFRP subjected to eccentric loads, Građevinar, 69 (7), pp. 573-580. DOI: 10.14256/JCE.1707.2016

[4] Al-Hadithy, L. and Al-Ani, M. (2017). Nonlinear Finite Element Analysis of RC Beams without Stirrups Strengthened by Longitudinal Soffit Bonded CFRP Strips for Shear, Al-Nahrain Journal for Engineering Sciences, 20(4), pp. 996–1004.

[5] Maaty, A., ELShami, A. and Kamel, F. (2022). Microstructure characterization of sustainable light weight concrete using trapped air additions, 62, pp. 194-211. DOI: 10.3221/IGF-ESIS.62.14

[6] Záleská, M., Pavlíková, M., Pokorný, J., Jankovský, O., Pavlík, Z. and Černý, R. (2018). Structural, mechanical and hygrothermal properties of lightweight concrete based on the application of waste plastics, Construction and Building Materials, 180, pp.1-11. DOI:10.1016/j.conbuildmat.2018.05.250.

[7] Almeshal, I., Tayeh, B., Alyousef, R., Alabduljabbar, H. and Mohamed, A. (2020). Eco-friendly concrete containing recycled plastic as a partial replacement for sand, Journal of Materials Research and Technology, 9(3), pp. 4631-4643. DOI: 10.1016/j.jmrt.2020.02.090.

[8] Aboul-Nour, L., Eisa, A. and El-Ghamry, A. (2023). Structural behavior of Lightweight and High strength Layered Hollow Core Slabs, Frattura ed Integrità Strutturale, 63, pp.134-152. DOI: 10.3221/IGF-ESIS.63.13.

[9] Shafigh, P., Jumaat, M. and Mahmud, H. (2010). Mix design and mechanical properties of oil palm shell lightweight aggregate concrete: A review, International Journal of the Physical Sciences, 5(14), pp. 2127–34.

[10] Sayadi, A., Neitzert, T. and Clifton, C. (2016). Feasibility of a biopolymer as lightweight aggregate in perlite concrete, World Academy of Science, Engineering, and Technology International Journal of Civil and Environmental Engineering., 10(9), pp. 751–761. DOI: 10.5281/zenodo.1124714.

[11] Bouali, M. and Hima, A. (2020). Alternative estimation of effective Young's Modulus for Lightweight Aggregate Concrete LWAC, Frattura ed Integrità Strutturale, 52, pp.82-97. DOI: 10.3221/IGF-ESIS.52.07.

[12] Colangelo, F. and Ilenia, F. (2019). Lightweight concrete with polyolefins as aggregates. Use of Recycled Plastics in Eco-efficient Concrete, Elsevier, pp. 167-187. DOI: 10.1016/B978-0-08-102676-2.00008-6.

[13] Muhammad, A., Bing, C. and Farasat, S. (2019). Investigate the influence of expanded clay aggregate and silica fume on the properties of lightweight concrete, Construction and Building Materials, 220, pp. 253-266. DOI: 10.1016/j.conbuildmat.2019.05.171.

[14] Chandra, S. and Berntsson, L. (2002). Lightweight Aggregate Concrete, Elsevier.

[15] Ke, Y., Beaucour, A. L., Ortola, S., Dumontet, H. and Cabrillac, R. (2009). Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of concrete, Construction and Building Materials, 23(8), pp. 2821–2828. DOI: 10.1016/j.conbuildmat.2009.02.038.
[16] Falliano, D., De Domenico, D., Sciarrone, A., Ricciardi, G., Restuccia, L., Ferro, G., Tulliani, J. and Gugliandolo, E. (2020). Influence of biochar additions on the fracture behavior of foamed concrete, Frattura ed Integrità Strutturale, 51, pp.189-198. DOI: 10.3221/IGF-ESIS.51.15.
[17] Falliano, D., De Domenico, D., Ricciardi, G. and Gugliandolo, E. (2018). Experimental investigation on the compressive strength of foamed concrete: Effect of curing conditions, cement type, foaming agent and dry density, Construction and Building Materials, 165, pp. 735-749. DOI: 10.1016/j.conbuildmat.2017.12.241.
[18] Panesar, D. (2013). Cellular concrete properties and the effect of synthetic and protein foaming agents. Construction and Building Materials, 44, pp. 575-584. DOI: 10.1016/j.conbuildmat.2013.03.024.
[19] Falliano, D., De Domenico, D., Ricciardi, G., Gugliandolo, E. (2018). Key factors affecting the compressive strength of foamed concrete, IOP Conference Series: Materials Science and Engineering, 431(6), p. 062009. DOI: 10.1088/1757-899X/431/6/062009.
[20] Marfia, S., Sacco, E. and Toti, J. (2010). An approach for the modeling of interface-body coupled nonlocal damage, Frattura ed Integrità Strutturale, 12, pp. 13-20. DOI: 10.3221/IGF-ESIS.12.02.
[21] Marfia, S., Sacco, E. and Toti, J. (2011). A coupled interface-body nonlocal damage model for the analysis of FRP strengthening detachment from cohesive material, Frattura ed Integrità Strutturale, 18, pp. 23-33. DOI: 10.3221/IGF-ESIS.18.03.
[22] Slate, S., Nilson, A. and Martinez, S. (1986). Properties of High-strength Lightweight Concrete, ACI Journal, 83(4), pp. 606-613. DOI: 10.14359/10454.
[23] Henkensiefken, R., Bentz, D., Nantung, T. and Weiss, J. (2009). Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions, Cement and Concrete Composites, 31(7), pp.427-437. DOI: 10.1016/j.cemconcomp.2009.04.003.
[24] Bentz, D. and Stutzman, P. (2006). Curing, hydration, and micro-structure of cement paste, ACI Materials Journal 103(5), pp. 348-356.
[25] Bentz, D. and Weiss, W. (2008). REACT: Reducing Early-Age Cracking Today, Concrete Plant International, 3, pp. 56–61.
[26] Shah, S. and Wang, K. (2004). Development of green cement for sustainable concrete using cement kiln dust and fly ash, International Workshop on Sustainable Development and Concrete Technology, pp. 15-23.
[27] Jensen, O., and Lura, P. (2006). Techniques, and materials for internal water curing of concrete, Materials and Structures, 39, pp. 817-825.
[28] Rao, C. and Darter, M. (2013). Evaluation of Internally Cured Concrete for Paving Applications, Final Report, Illinois, ESCSI, p. 108.
[29] Alaa, R. (2018). Lightweight expanded clay aggregate as a building material – An overview, Construction and Building Materials, 170, pp. 757-775. DOI: 10.1016/j.conbuildmat.2018.03.009.
[30] Chaimahawan, P. (2009). Seismic Retrofit of Substandard RC Beam-Column Joints by Planar Joint Expansion, Ph.D. Thesis, Thammasat University, p. 193.
[31] Harba, I. and Abdulridha, A. (2021). Numerical analysis of RC columns under cyclic uniaxial and biaxial lateral load, Građevinar, 73 (10), pp. 979-994, DOI: 10.14256/JCE.2889.2020.
[32] Harba, I., Abdulridha, A. and AL-Shaar, A. (2022). Numerical analysis of high-strength reinforcing steel with conventional strength in reinforced concrete beams under monotonic loading. Open Engineering, 12(1), pp. 817-833. DOI: 10.1515/eng-2022-0365.