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The Influence of a Damaged Concrete Cover on the Behavior of a Simply-Supported Beam

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Abstract

The concrete cover is a part of the concrete that provides the required protection for the reinforcing steel within the required element from external effects. This concrete cover can be damaged for an assortment of reasons, one of which is environmental factors. As a result, this research focused on the effect of worn concrete covering on the structural response of beams. Moreover, the possibility of repairing or replacing this concrete cover with a cement material was done by testing seven beams with the exact dimensions (2700 mm long, 250 mm deep, and 140 mm wide). The first specimen was a control specimen, while in the remaining specimens, a part of the concrete cover was removed in the midspan region with a length of 600 mm and in different formats. The part below the neutral axis (tension zone) was removed in the first two specimens. The part above the neutral axis (the compression zone) was removed in the second two specimens. The whole cover was removed within the specified distance for the other two specimens. In one out of every two of these six specimens, the removed concrete cover was replaced with cementitious material. A flexural test was performed for all specimens, and the conclusion was reached that damaging or removing the concrete cover from the tensile region (below the neutral axis) is less harmful than from the compression region since the beam is often designed as a cracked section. Also, removing the concrete cover from the compression region gives cracks a greater width than removing the concrete cover from the tension region at the same loading level. In the case of replacing the concrete cover with a cementitious one, if the replacement is in the compression zone, it will result in cracks when loading with a width greater than that of the rest of the cases. For specimens that removed their concrete covers from the tension zone, compression zone, and the whole section, the failure loads decreased by 39%, 20%, and 23%, respectively, concerning the control beam. In contrast, all these specimens were repaired with cementitious materials, with an ultimate load capacity approximately equal to the control beams. From these results, any damaged concrete cover for beams in any zone with cementitious materials having high strength and a good bond with old concrete sections can be repaired.

Keywords: Reinforced Concrete; Simply-Supported Beam; Concrete Cover; Repairing.

1. Introduction

A sufficient concrete cover must be provided in reinforced concrete structures to safeguard the reinforcement from a corrosive environment, protect steel from excessive temperatures such as fire, and ensure that reinforcement can be involved effectively without slipping when loaded. The concrete cover is the shortest distance between the surface of the embedded reinforcement and the concrete's outer surface. This concrete cover can be damaged due to weather, accidents, or other effects. So this study focused on the effect of concrete cover on the behavior of reinforced concrete beams and the effectiveness of their repair. Rahal [1] conducted a study in 2006 to determine the influence of increasing the thickness of the concrete side cover on the shear behavior of reinforced concrete beams. At the ultimate conditions, cracking was observed in specimens with relatively large covers. However, it was restricted to the corners of the section,

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having left much of the cover on the vertical side. Zakaria et al. (2009) [2], through an experimental study on seventeen specimens, found that shear reinforcement characterization (concrete side cover to stirrup, stirrup spacing, and stirrup configuration) and longitudinal reinforcement ratio influence diagonal crack spacing and width.

Six reinforced concrete beams with varying concrete covers (25 mm and 30 mm) were tested by Wakchaure et al. (2012) [3]. The researchers found that the increase in crack width is directly proportional to the increase in the thickness of the concrete cover. He & Cheng [4] studied the validity of using the BFRP grid to control crack development and improve its distribution in concrete beams with thick cover. This technique leads to a decrease in the crack width and an increase in the number of cracks. Zhang et al. [5] conducted an experimental study in 2018 to study the effect of reinforcement corrosion under sustained load on the development and width of cracks in reinforced concrete beams. They found that the effect of reinforcement corrosion on transverse crack spacing is not apparent, but it has a clear effect on the evolution of transversal crack width.

Khalaf & Huang (2018) [6] studied some factors (steel bar yielding, concrete cover, concrete compressive strength, and concrete spalling) that affected the bond between concrete and reinforcement within reinforced concrete beams. The concrete cover provides confinement that enhances the bond between the steel bar and the concrete. Khiyon et al. (2019) [7] studied the effect of the concrete cover thickness containing a percentage of garnet on the reinforcing steel by conducting ultrasonic and tensile tests. They found that the concrete cover with a thickness of 30 mm provides good protection for the reinforcing steel up to 300 degrees Celsius. Also, replacing sand with garnet by 40% gives good fire resistance.

An experimental study was conducted by Muhdin (2019) [8] to investigate the effect of concrete cover on the reinforced concrete members under pure torsion. He found that the concrete cover's thickness significantly impacts the members' utmost strength and, as a whole, their behavior. Wang et al. (2019) [9] conducted push-out tests to investigate failure modes, bond stress-slip curves, and composite steel-concrete section strain distribution. The results indicate that the increase in concrete cover thickness could significantly improve the bond strength of the steel section encased in concrete due to the enhancement in the concrete confining effect.

The effect of concrete cover on the torsional behavior of beams was studied by Ibrahim et al. [10]. The experimental results revealed that the concrete cover significantly affects reinforced concrete members' maximum capacity and overall torsional characteristics. Vishal & Satyanarayanan (2023) [11] conducted an experimental study to find the optimal concrete cover thickness for beams and columns under an elevated fire scenario. The concrete cover thickness significantly affects the member's structural behavior. Also, some previous studies show that columns have better thermal performance than beams [12–16].

Through what was found and what was mentioned above, we did not find that there is a study concerned with the effect of repairing the concrete cover by replacing it in whole or in part with a material other than ordinary concrete on the structural behavior of the member and how much it will recover from its maximum strength. Therefore, we will focus this study on this aspect.

2. Martials and Methods

The following flowchart (Figure 1) explains the methodology adopted to achieve the present study.

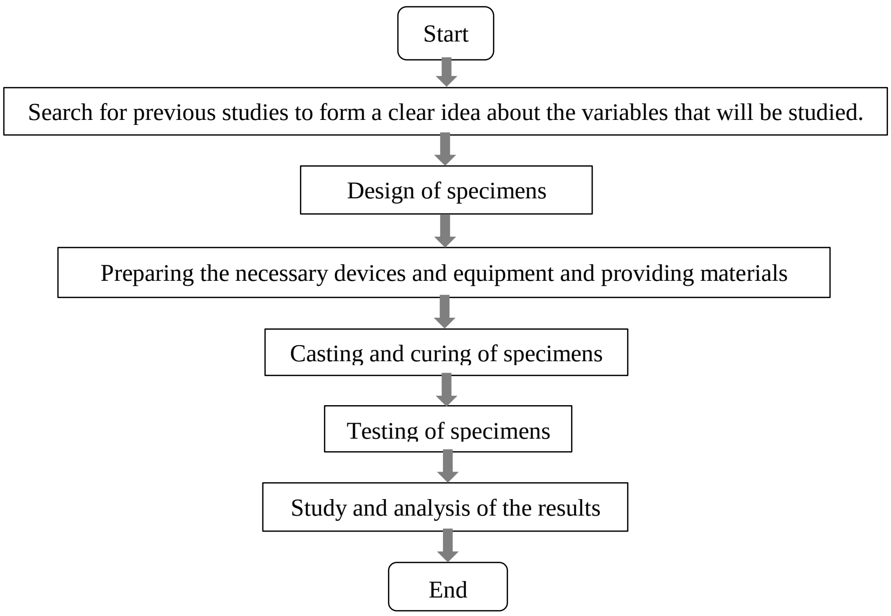
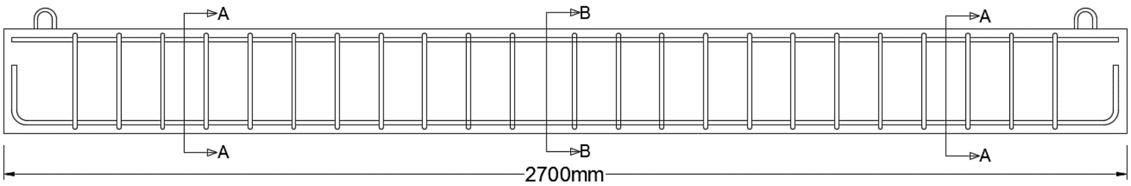


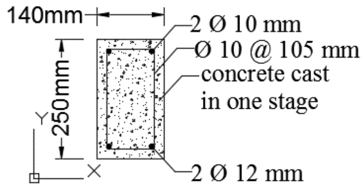
Figure 1. Flowchart of the methodology

2.1. Specimens Information

Seven reinforced concrete backed-up beams will be tested experimentally, with dimension and cross-section characteristics as depicted in Figure 2 and Table 1.



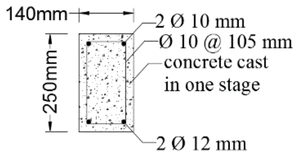
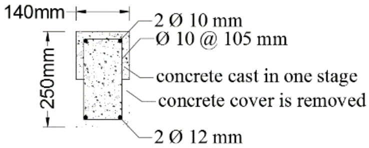
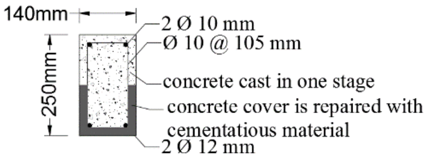
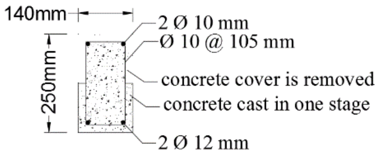
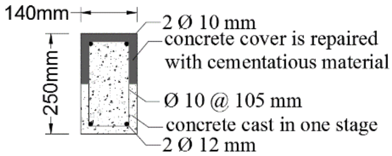
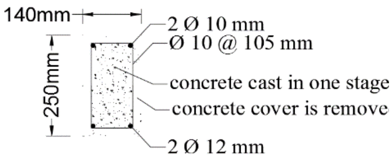
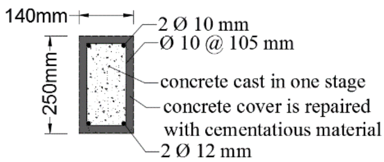
Longitudinal section



Cross section A-A

Figure 2. Dimensions and details of longitudinal section and cross-section A-A of all specimens

Table 1. Midspan cross-section (section B –B) for all specimens

Specimen	Cross section B-B
CSSB	
CSSBLU	
CSSBLUR	
CSSBUU	
CSSBUUR	
CSSBAL	
CSSBALR	

Specimen CSSB is the control specimen. All other specimens are similar to the control specimen in terms of reinforcement and dimensions, but a part of the concrete cover is removed in the midspan to simulate the effect of external environmental conditions on damaging the concrete cover and then study its effect on the behavior of the specimen. As well as studying the benefit of repairing the damaged concrete cover by replacing it with cementitious material, as shown in Figure 3. Specimen CSSBUU has the concrete cover in the midspan upper U zone removed at a distance of 600mm. Specimen CSSBUUR is the same as specimen CSSBUU, but the cementitious material used to replace the concrete coat in the upper U zone at midspan has a length of 600 mm. The concrete cover is removed from the lower U zone at midspan along a 600 mm distance for specimen CSSBLU. The cementitious material is used to fill the place where the concrete cover is removed, as in specimen CSSBLUR, which is like specimen CSSBLU. In the specimen CSSBAL, all concrete cover is removed at midspan, at a distance of 600mm. Specimen CSSBALR is similar to specimen CSSBAL, but the cementitious material is used instead of concrete cover at midspan with a distance equal to 600 mm.

Figure 3. Cementitious material and its solvent liquid from DCP Company

2.2. Specimens Casting and Treating

All specimens will be cast in one stage with concrete having a cylindrical strength (33 MPa). The specimens were labeled and coated with moistened sacks after 24 hours (See Figure 4).

(a) (b) (c)

Figure 4. (a)-Wooden molds and steel cage. (b)-Casting process. (c)-Curing process

For specimens with a region that will be put in a cementitious material instead of concrete cover, After 28 days, a scarifying machine with a revolving disc wheel is used to clean and roughen the old concrete surface before the application of the new material.

2.3. Specimens Examination

For all test specimens, the load is placed as a two-point load. When the load is applied up to failure, one dial gauge is situated to track the mid-span deflection (Figures 5 and 6).

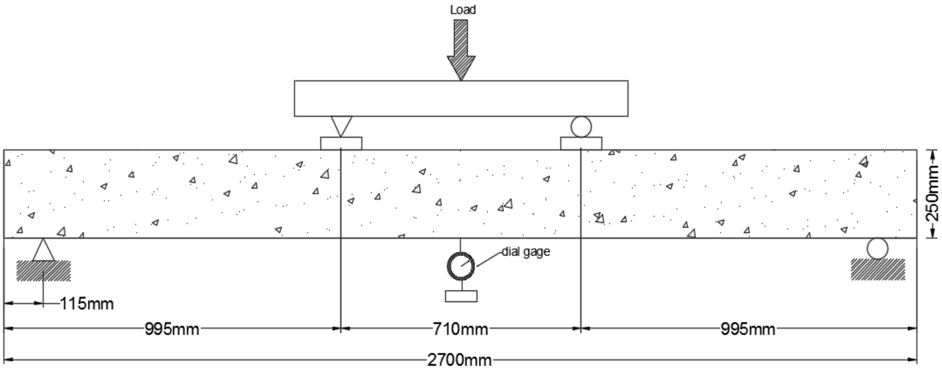


Figure 5. Flexure test

Figure 6. Flexure test machine

3. Test Results and Discussions

Load deflection curves, first cracking load, maximum load, defeat modes, and cracking motifs are all included.

3.1. Curves of Load Deflection

The load midspan deflection for all specimens is shown in Figures 7 to 9. Tables 2 and 3 and Figures 10 and 11 show the first cracking load, crack width, maximum load, and mid-span deflection at the ultimate load of all specimens.

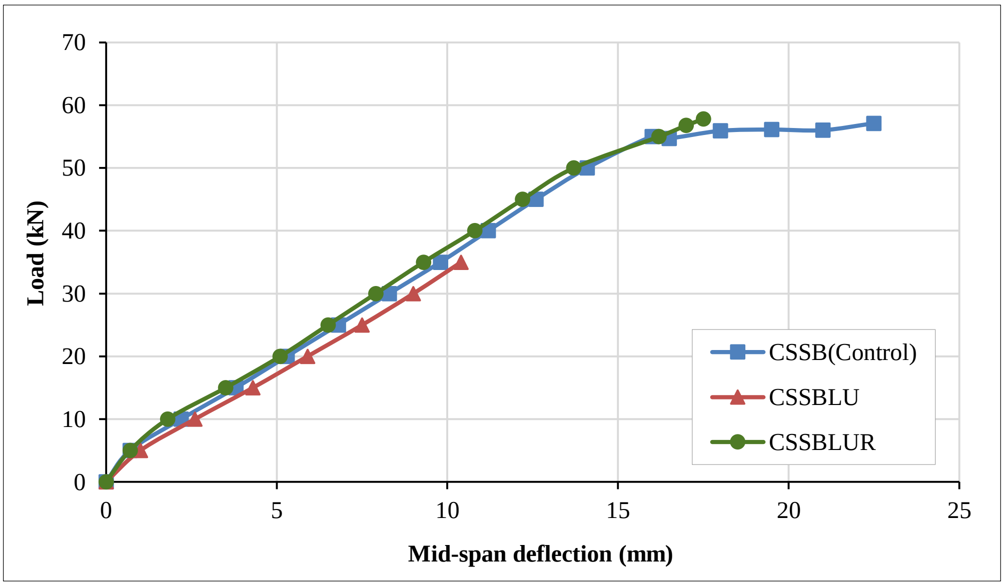


Figure 7. Load-deflection curve for specimens CSSB, CSSBLU, and CSSBLUR

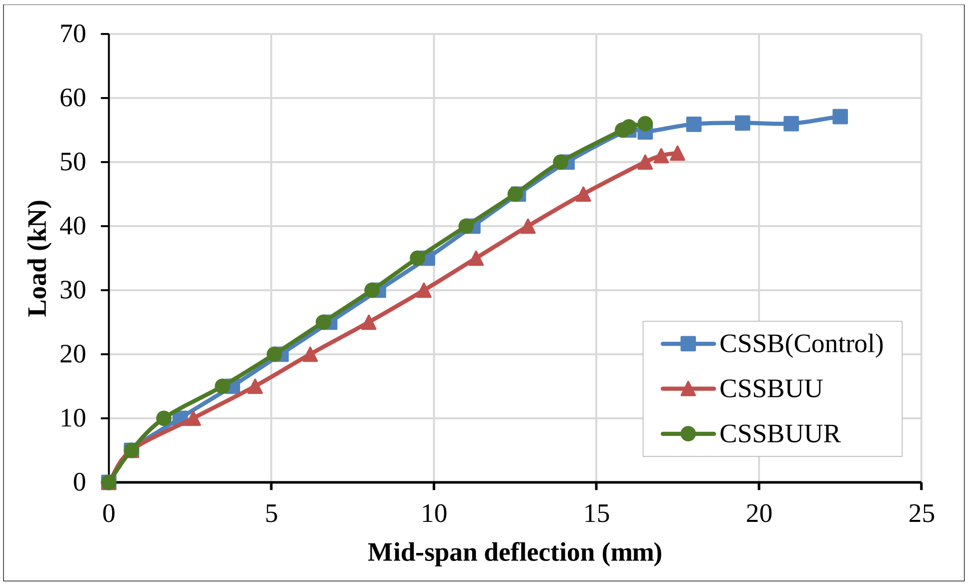


Figure 8. Load-deflection curve for specimens CSSB, CSSBUU, and CSSBUUR

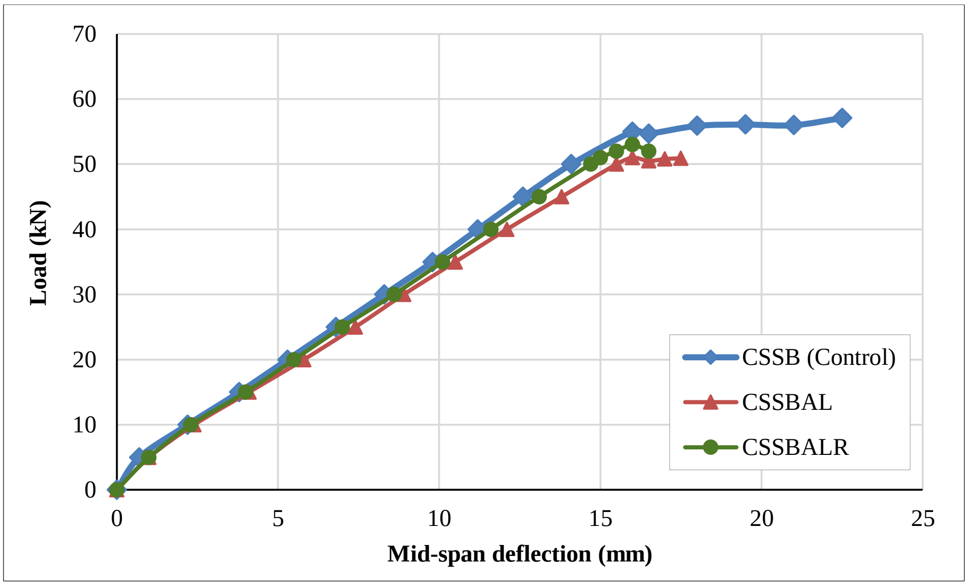


Figure 9. Load-deflection curve for specimens CSSB, CSSBAL, and CSSBALR

Table 2. Specimens' first cracking load, failure load, and mid-span deflection at failure load

Symbol of a specimen	Characterization of the specimen	The initial cracking load (kN)	The failure load (kN)	Failure-induced mid-span deflection (mm)
CSSB	Simply-supported reinforced concrete beam, control specimen.	6.3	57.1	22.5
CSSBLU	Simply-supported reinforced concrete beam with concrete cover in the upper mid-span U-zone removed to a distance of 0.6 meters.	3.0	35.0	10.4
CSSBLUR	Simply-supported reinforced concrete beam with concrete cover in the lower mid-span U-zone removed to a distance of 0.6 meters and repaired by cementitious material.	9.3	57.8	17.5
CSSBUU	Simply-supported reinforced concrete beam with concrete cover in the upper mid-span U-zone removed to a distance of 0.6 meters.	5.5	45.4	17.5
CSSBUUR	Simply-supported reinforced concrete beam with concrete cover in the upper mid-span U-zone removed to a distance of 0.6 meters and repaired by cementitious material.	7.0	56.0	16.5
CSSBAL	Simply-supported reinforced concrete beam with all concrete cover in the mid-span removed to a distance of 0.6 meters.	7.5	43.9	17.5
CSSBALR	Simply-supported reinforced concrete beam with all concrete cover in the mid-span removed to a distance of 0.6 meters and repaired by cementitious material.	8.0	52.0	17.0

Table 3. All specimens' load and cracking width

CSSB		CSSBLU		CSSBLUR		CSSBUU		CSSBUUR		CSSBAL		CSSBALR	
Load (kN)	Crack width (mm)	Load (kN)	Crack width (mm)	Load (kN)	Crack width (mm)	Load (kN)	Crack width (mm)	Load (kN)	Crack width (mm)	Load (kN)	Crack width (mm)	Load (kN)	Crack width (mm)
10.8	0.04	9.0	0.02	9.3	0.02	5.5	0.02	7.0	0.02	10.0	0.02	12.0	0.02
13.8	0.06	14.0	0.04	13.3	0.04	10.0	0.04	10.0	0.06	14.0	0.04	15.0	0.04
17.8	0.10	19.0	0.08	18.3	0.06	14.0	0.08	14.0	0.10	19.0	0.08	19.0	0.10
23.8	0.12	23.0	0.10	22.3	0.10	18.0	0.10	19.0	0.14	22.0	0.10	22.0	0.14
30.8	0.16	29.0	0.16	28.3	0.12	24.0	0.16	23.0	0.16	27.0	0.14	27.0	0.22
32.8	0.20	34.0	0.20	32.3	0.16	30.0	0.20	28.0	0.20	35.0	0.20	32.0	0.26
39.8	0.22			38.3	0.20	36.0	0.24	39.0	0.30	41.0	0.24	40.0	0.32
44.8	0.28			43.3	0.24	43.0	0.32	46.0	0.42			45.0	0.34
49.8	0.30							51.0	0.46			49.0	0.34
54.8	0.40							55.0	0.50				
55.8	0.62												

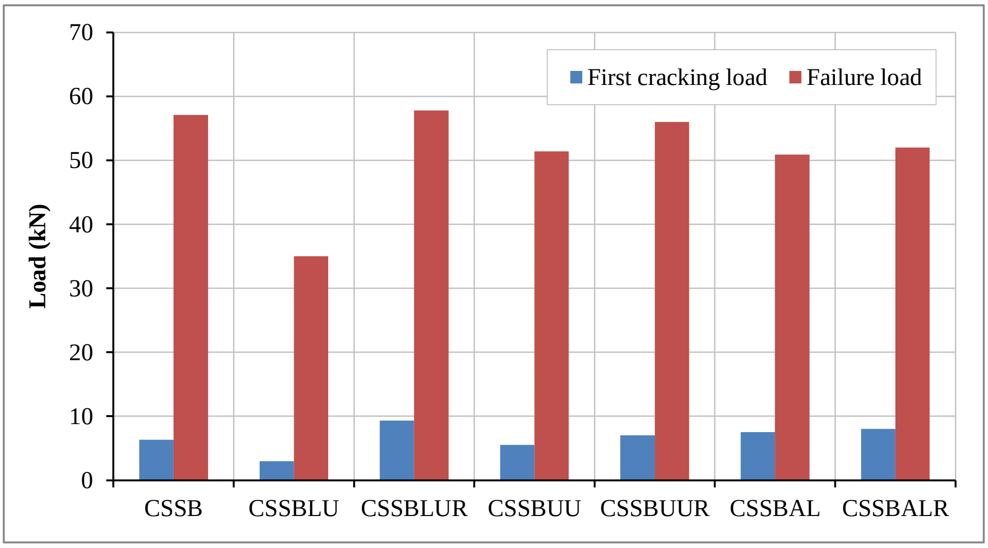


Figure 10. Utmost loads and first cracking loads for all specimens

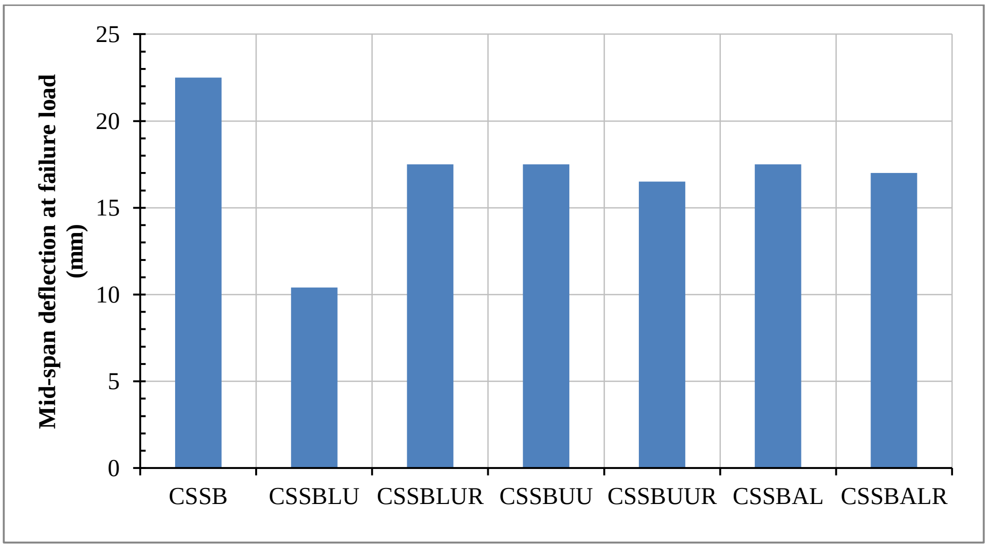


Figure 11. All specimens' mid-span deflection at failure loads

As shown in Figure 5, the utmost flexural moment equals (0.44 Pu) at mid-span. For CSSB (control specimen):

d = 225 mm is the efficient depth for tension reinforcement

As = 226 mm^2

The effective depth for compressive reinforcement d' =25 mm, As' =158 mm^2

$$\rho' = \frac{As'}{bd} = \frac{158}{140*225} = 0.005 \tag{1}$$

$$\rho_b = 0.85^2 \frac{fc'}{fy} \frac{600}{600+fy} = 0.85^2 \frac{33}{400} \frac{600}{600+400} = 0.0358 \tag{2}$$

$$\rho'_{cy} = 0.85\beta_1 \frac{fc'}{fy} \frac{d'}{d} \frac{600}{600-fy} + \rho' = 0.85 * 0.814 * \frac{33}{400} \frac{25}{225} \frac{600}{600-400} + 0.005 = 0.024 \tag{3}$$

$$\rho = \frac{As}{bd} = \frac{226}{140*225} = 0.00717, \therefore\ \rho < \rho'_{cy} \text{ the compressive reinforcement not reach the yield} \tag{4}$$

$$s' = 600 - (600 + fy)\frac{d'}{d} = 600 - (600 + 400)\frac{25}{225} = 488.9 \text{ MPa} > \text{fy}, \therefore fs' = 400 \text{ MPa} \tag{5}$$

$$\rho'_b = \rho_b + \rho' = 0.0358 + 0.005 = 0.0408 \therefore \rho < \rho'_b, \text{ the tensile reinforcement reach to the yield.} \tag{6}$$

$$K_1 = \frac{As\ fy - 600\ As'}{0.85\ \beta_1 fc' b} = \frac{(226*400)-(600*158)}{0.85*0.814*33*140} = -1.376 \tag{7}$$

$$K_2 = \frac{600\ As' d'}{0.85\ \beta_1 fc' b} = \frac{600*158*25}{0.85*0.814*33*140} = 741.418 \tag{8}$$

$$C = \frac{K_1 + \sqrt{K_1^2 + 4K_2}}{2} = \frac{-1.376 + \sqrt{(-1.376)^2 + (4*741.418)}}{2} = 26.55 \text{ mm} \tag{9}$$

$$a = \beta_1 c = 0.814 * 26.55 = 21.6 \text{ mm}, fs' = \frac{c-d'}{c} * 600 = \frac{26.55-25}{26.55} * 600 = 35.02 \text{ MPa} \tag{10}$$

$$Mn = 0.85fc'ab\left(d - \frac{a}{2}\right) + As'fs'(d - d') = \left(0.85 * 33 * 21.6 * 140 * \left(225 - \frac{21.6}{2}\right)\right) + \left(158 * 35.02 * (225 - 25)\right) = 19284639 \text{ N.mm} = 19.28 \text{ kN.m (Ferguson 1981) [17].} \tag{11}$$

$$0.44Pu = 0.9 * 19.28\ , Pu = 39.4 \text{ kN} \tag{12}$$

The theoretical load of 39.4 kN is about 69% of the ultimate experimental load of the control beam CSSB specimen (57.1 kN). The differences in first cracking, failure load, and mid-span deflection at failure load for all specimens concerning CSSB are listed in Table 4. The control specimen CSSB defeats at load (57.1 kN) while the ultimate theoretical capacity is (39.4 kN). The mid-span deflection at defeat is (22.5 mm).

Table 4. Differences in specimens' first cracking load, failure load, and mid-span deflection at failure load compared to the control specimen (CSSB)

Symbol of a specimen	% difference in first cracking load	% of failure load difference	% difference in mid-span deflection at failure
CSSBLU	-52	-39	-54
CSSBLUR	48	1	-22
CSSBUU	-13	-20	-22
CSSBUUR	11	-2	-27
CSSBAL	19	-23	-22
CSSBALR	27	-9	-24

By observing Figure 7, we can see that the specimen CSSBLU failed at a load of 35 kN and a deflection of 10.4 mm, less than the sample CSSB by 39% and 54%, respectively. The CSSBLUR specimen failed at a load of 57.8 kN and a deflection of 17.5 mm. That is, the specimen gave a little increase in ultimate strength relative to the CSSB specimen, and it also gave less deflection by 22%.

The CSSBUU specimen failed at a load and deflection of 45.4 kN and 17.5 mm, respectively, 20% and 22% lower than the control specimen. The CSSBUUR beam failed at a load of 56 kN (2% less than the control) and a deflection of 16.5 mm (27% less than the control). (Figure 8).

The CSSBAL specimen failed at a load of 43.9 kN, which is 23% less than the CSSB control specimen, and with a deflection of 17.5 mm, which is also 22% less. The CSSBALR specimen failed at a load of 52 kN, which is 9% less than the CSSB specimen, and gave a deflection of 17 mm, 24% less than the CSSB specimen.

3.2. Cracking Pattern

The crack pattern of all specimens is shown in Figure 12. For the control specimen (CSSB), the first crack started at a load of 6.3 kN, being in the middle of the distance between the load drop point and the left support from the bottom and vertically, followed by the appearance of cracks in the lower face of the specimen at the load points, then in the middle of the distance between the load points (midspan). Then the condition developed through the appearance of new cracks along the distance between the supports and the widening and extension of the old cracks. Most of the cracks were vertical, except those close to the supports, which were inclined at 45 degrees. The increase in loading led to the widening and propagation of the cracks, leading to flexural failure.

Figure 12. Crack pattern

Cracks in the CSSBLU specimen began to appear between the loading points and the supports, followed by vertical cracks in the zone between the vertical loading points. Some cracks appeared near the supports, and with increasing loading, the cracks began to expand and spread, reaching a state of flexural failure. The appearance of the first crack in the CSSBLUR specimen was late relative to the first crack in the control specimen CSSB, and the shape and propagation of cracks are similar to the CSSBLU specimen and the control specimen CSSB at the same loading level. The type of failure is a flexural failure.

When the load reached 5.5 kN in the CSSBUU specimen, vertical cracks appeared in the midspan. When the load was increased, these cracks began to widen and rise upward, with diagonal cracks appearing between the loading points and the supports. Then the cracks began to expand and spread until they reached flexural failure. The specimen CSSBUUR has almost the same behavior as the specimen CSSBUU in terms of the shape and propagation of cracks. However, the cracks appeared in it later than in the specimen CSSBUU and the specimen CSSB, and the width of the cracks in it is less than both. A further failure form is a flexural failure.

In the CSSBAL specimen, cracks began to appear in the midspan with a 7.5 kN load, then following an increase in load, these cracks began to rise vertically to the top. With the emergence of new cracks in the region between the loading points and the supports, at first they were vertical, then with the increasing load, they rose to the top diagonally. Then the cracks increased in width and spread with increasing loading, leading to flexural failure. For the CSSBALR specimen, cracks began to appear at a load of 8 kN. The appearance of cracks was almost below the loading points, and with increasing loading, other cracks appeared in the zone between the loading points and the supports, as well as in the midspan, but with fewer numbers than in the CSSBAL specimen. With increasing loading, the cracks in the midspan tended almost vertically towards the top. However, the cracks in the region between the supports and the loading points were directed upwards obliquely, and the form of failure was also flexural.

4. Conclusions

The concrete cover plays an essential role in protecting the reinforcing steel from external influences and affects the structural behavior of the elements, which was observed during this laboratory study. Where the presence or absence of the concrete cover affects the location of the neutral axis and thus affects the stress values in the concrete and the reinforcing steel, which affect the shape, location, width, and propagation of cracks from the laboratory work done, the following can be noted:

- Damaging or removing the concrete cover from the tensile area (below the neutral axis) is less harmful than from the compression area since the beam is often designed as a cracked section.
- At the same loading level, removing the concrete cover from the compression region results in wider cracks than removing the concrete cover from the tension region.
- In the case of replacing the concrete cover with a cementitious material from DCP Company, if the replacement is in the compression zone, it will give cracks when loading with a width more remarkable than the rest of the cases.
- If concrete covers are removed from the tension zone, compression zone, and whole section, the failure loads decrease by 39, 20, and 23%, respectively, concerning the control beam due to reducing effective depth.
- All these specimens were repaired with cementitious materials and produced good behavior, with the ultimate load capacity at failure approximately equal to the control beams.
- From these results, damaged concrete covers can be repaired with a special material having high concrete strength and a good bond between old and new concrete for structural members.

5. Nomenclature

a: depth of equivalent rectangular stress bloc	As; Area of steel reinforcement
As': area of compression reinforcement	b: width of compression face of member
c: distance from extreme compression fiber to the neutral axis	d: distance from extreme compression fiber to centroid
d′: distance from extreme compression fiber to centroid	f'c: specified compressive strength of concrete
fs: tensile stress in reinforcement at service loads, excluding pre-stress reinforcement, psi	fs′: compressive stress in reinforcement under factored loads
fy: specified yield strength for reinforcement	Mn: nominal flexural strength at section reinforcement ratio
Pu: factored load	β1: factor relating depth of equivalent rectangular compressive stress block to depth of neutral axis
ρ: ratio of As to bd	ρb: balanced reinforcement ratio
ρ′: ratio of As′ to bd	

6. Declarations

6.1. Author Contributions

Conceptualization, K.K.S., B.I.A., and M.J.K.; methodology, K.K.S., B.I.A., and M.J.K.; software, B.I.A.; validation, B.I.A. and M.J.K.; formal analysis, K.K.S.; investigation, K.K.S., B.I.A., and M.J.K.; data curation, K.K.S. and M.J.K.; writing—original draft preparation, K.K.S. and B.I.A.; writing—review and editing, M.J.K.; visualization, K.K.S., B.I.A., and M.J.K.; supervision, K.K.S., B.I.A., and M.J.K..; project administration, K.K.S., B.I.A., and M.J.K.; All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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