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Behavior Investigation of Arch Beams Using Different Types of Strengthening Methods

[1]Saadi M. Al-Dabbagh, [2]Dr. Suhaib Y.K. Al-Darzi

[1]M.Sc. Student, University of Mosul, College of Engineering, Civil Engineering Department, Mosul, Iraq

[2]Assistant Professor, University of Mosul, College of Engineering, Civil Engineering Department, Mosul, Iraq

Email: [1]saadi.20enp100@student.uomosul.edu.iq, [2]suhaib.qasim@uomosul.edu.iq

***Abstract* - Arched beams are exposed to different types of damage, including cracks in the arch structure due to the structure's age, increased applied loads, environmental conditions, and human activities such as an explosion. An opening caused by missile strikes represents damage to the arch beam. In this study, five models were fabricated and tested experimentally. A standard model had no damage, the second had an opening repaired by polymeric cement mortar, and the third had an opening repaired by polymeric cement mortar and reinforced by polymeric carbon fibers. The fourth model had a crack repaired by injecting with epoxy and strengthened with Carbon Fiber-Reinforced Polymers (CFRP) parallel to the crack. At the same time, the fifth specimen had a crack repaired by injecting it with epoxy and strengthening by (CFRP) perpendicular to the crack. All specimens were tested using a single point load at mid-span.**

It was found that the repairing specimen opening by injecting cement mortar and strengthening by polymeric carbon fibers give resistance more than the second specimen by about (3.3%). The failure load of the fifth model was greater by (2.78 %) than the fourth specimen.

Keywords: Arched beams, Fracture load, Failure load, Injection epoxy, Polymerized cement mortar.

I. INTRODUCTION

In many different structures, arch beams support the applied loads, as those usually used in bridges. The reinforced concrete arch beam can suffer many types of damage, such as crushing or cracking.[1] Therefore, it is essential to determine the quick and effective restoration techniques needed to maintain the durability and capability of these structures to resist the loads applied.[2] Ali, Y. A., and Kadhum, M. J., 2015 investigated hollow arched beams supported by hinge-roller with and without openings. Various locations and shapes of openings are reinforced and unreinforced by internal confinement steel reinforcement. The study confirmed that these variables affected the ultimate capacity of the beams and maximum horizontal displacement. They found that the models not reinforced with rebar reduced their maximum resistance load by (46%), and the loading capacity reduced by (40%) depending on the presence of openings.[3] Ali, A. Y., and Hamza, B. A., 2015, conducted an experimental study of reinforced concrete arch beams with or without openings in various locations, with internal reinforcing rebar to confine around the openings or by polymeric carbon fibers. They compared the results with the theoretical analysis and found that the difference between the maximum load and the cracking load is (5.83%) and (3.92%), respectively.[4] Since Fiber Reinforced Polymers (FRP) have been widely employed to improve the strength or repair damaged arch structures. Zhang X. et al., 2015, used the intrados bonding approach to compare the strength of the bonding/anchoring method. They encountered that; the arch beams reinforced with carbon fiber resist four times those of regular reinforced concrete beams. The reinforcing efficiency was determined according to the strengthening. The wrapping method was considered the best, as it provided a higher level of strengthening efficiency. The load-bearing increased by about (40%). On the other hand, the bonding approach was considered worse and decreases efficiency by (20%). The peeling stress and shear stress control the debonding of carbon fiber reinforced polymer fibers near the center of the arch.[5] Hamed, E. et al., 2015 conducted an experimental and analytical study using Carbon Fiber Polymeric strips (CFRP strips) strengthening in the middle of the inner and outer faces of the arch beam. They also tested another beam by adding (CFRP sheets) at the ends of the CFRP strips. They also reinforce the arch in the compressive area on both sides with the CFRP strips. The results showed that using CFRP reinforcing system increase the bearing capacity of the arch beam.[6] Jayaramappa, N. 2016, conducted tests to fully understand the behavior of arch and straight hollow ferrocement reinforced concrete beams. Compared to ferrocement beams, conventional steel reinforcement showed better strength in the first crack and maximum failure. Due to the ferrocement's high ductility, the bending stress calculations for the ferrocement beam performed better than the standard reinforced concrete beam.[7] The use of Ultrahigh-Performance Fiber-Reinforced Concrete (UHPFRC) in the arch beam was investigated by Yang, J. et al. 2019 by conducting experimental tests and theoretical study using the finite element method. The arch

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beam with (UHPFRC) compared with the normal concrete (NC) arch beam, which had a higher resisting load and better crack reduction ability.[8] Subramanian, R., and Murugesan, A., 2019 utilized a frame model consisting of an arch part and a straight horizontal part. The study estimate how much horizontal thrust the arch will exert on the supports as the central load increases.[9]

II. MATERIALS

Tools, equipment, and materials were used in the laboratory to conduct the adopted experimental program. All tests were conducted in the Materials Testing Laboratory at the College of Engineering, University of Mosul, in the Civil Engineering Department. Properties of materials forming the concrete used in the study were clarified and compared with the related specifications.

2.1 Concrete Mixture Materials

Normal reinforced concrete was used to casting arch beams with cement produced by the "Mass" factory in Iraq, which matched the Ordinary Portland Cement (Type 1). River sand matching the British Standards (BS 882:1992) was used.[10] The round river coarse aggregate was graded with a maximum size of (19mm) according to British Standards (BS 882:1992).[10]

2.2 Concrete Mechanical Properties

The concrete mixture was prepared using a weight ratio of (cement: sand: gravel/water) (3:1.5:1/0.4) according to British Standards (BS 1881-116). [11] Standard concrete cubes with dimensions of (150mm×150mm×150mm) were cast, cured, and tested at (28 days). They had an average compressive strength of (32.5 MPa). American specifications (ASTM C496/C496M-11) [12], standard concrete cylinders with dimensions of (150mm×300mm) were cast, cured, and tested for splitting at (28 days). They had an average tensile splitting strength of (2.852MPa).Simple concrete beams with cross-section dimensions of 100mmx100mm and length of (500mm) were tested at the age of (28 days) to determine the concrete flexural strength according to American specifications (C293/C293M-10) [13], which was found to be (4.575 MPa).

2.3 Reinforcement Properties

The (12mm) diameter bars were used as a longitudinal reinforcement, and stirrups were formed using (10mm) diameter bars. The properties of the reinforcement steel bars, listed in Table (1), meet the American specifications (ASTM A615M). [14]

Table 1: Properties of steel reinforcement

Nominal diameter. (mm)	Calculated diameter. (mm)	(fy). (MPa)	(fu). (MPa)	Elongation. (%)
12	11.637	583	678	14
10	9.768	590	688	12.66

2.4 Repairing Cement Mortar Properties

A one-component, fiber-reinforced polymerized cement mortar (Cempatch S) with a compressive strength greater than (60 MPa) at (28 days), flexural strength greater than (60 MPa) at 28 days, and tensile strength greater than (3 MPa) at (28 days) was used in concrete repair. The cement mortar's binding material used in this study was a two-component, "solvent-free epoxy" adhesive that can be applied on old concrete or cement surfaces to provide a long-lasting and complete connection with freshly placed cement mortar. [15]

2.5 Injection Epoxy Properties

Two-component low viscosity epoxy (Quickmast 105) with a compressive strength greater than (70 MPa) at (7 days), flexural strength greater than (50 MPa) at (7 days), and a tensile strength greater than (25 MPa) were used to inject cracks. [16]

2.6 Carbon Fiber Reinforced Polymers Properties

The (CFRP) sheet consists of carbon fibers with a thickness of (0.167mm), a laminate tensile strength of (3500 MPa), and a polymer resin (epoxy), a two-component epoxy material. [17]

III. REINFORCEMENT DETAILS OF THE CONCRET ARCHES

The study considered five arches of reinforced concrete beams with cross-sections of (300 mm) in height and (150 mm) in width. The arch beams rest on vertical supports (Column) had the same properties as the arch. The first sample is a standard reinforced concrete arch (S).The remaining four reinforced concrete arches were: an arched reinforced concrete with an opening repaired with a special cementitious repair mortar only (Hc1); an arched reinforced concrete with an opening repaired with a special cementitious repair mortar and strengthened with (CFRP) (Hc2); an arched reinforced concrete with a crack injected with epoxy and strengthened with (CFRP) parallel to the crack (Ic1); and an arched reinforced concrete with a crack injected with epoxy and strengthened with (CFRP) (Ic2). All reinforced concrete arches were constructed with circulator beams and vertically straight columns, as shown in Figure (1). Two bars of (12mm) diameter at the top and bottom were used as the main

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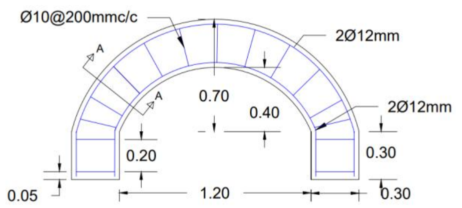
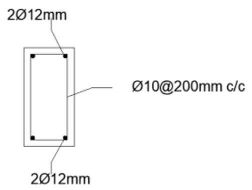
reinforcement. Closed stirrups with a diameter of 10mm spaced at (200mm). The beam reinforcement is shown in Figure (1).



Longitudinal Section



Section (A-A)

Figure 1: **Reinforced concrete arches dimensions and steel reinforcement details. (Dimensions of the drawing are in meters)**

IV. PREPARATION OF THE SAMPLES AND TEST PROCEDURE

After the preparation and casting of the standard model, the opening specimens were prepared for casting. Cube cork of (100mm x100mm x150mm) was placed at the quarter length of the arch before casting the two specimens with the opening (Hc1 and Hc2), as shown in Figure (2). After (24) hours following the casting of the specimens, the wet canvas was used to cover each specimen for (28) days. After (28) days, an epoxy binder was applied to the surface of the concrete to treat the opening specimens. After that, the opening was repaired by filling it using cement mortar.

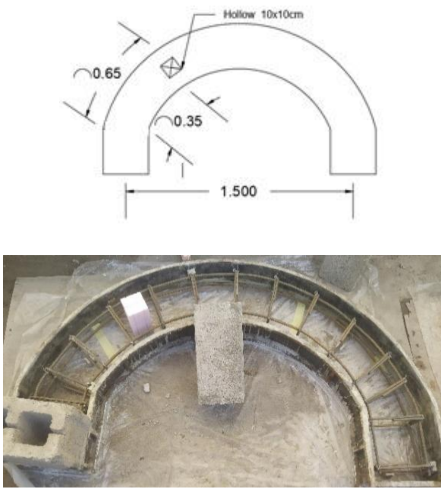


Figure 2: Preparing the opening specimens (Hc1 and Hc2). (The drawing's dimensions are in meters)

The specimens with cracks (Ic1 and Ic2) were created by placing a (1.0 mm) thickness plate along the beam before concrete casting. The plate was removed after six hours of concrete casting. The crack's locations and shapes are shown in Figure (3). The same curing procedure was used, and then at (28) days, an epoxy resin was used to inject the cracks. The specimen (Hc2, Ic1, and Ic2) was then wrapped with a (CFRP) sheet, as shown in Figure (4).

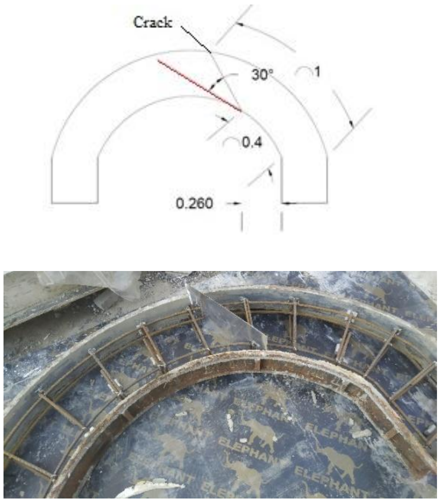
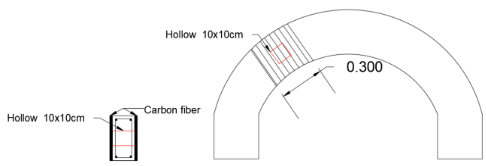
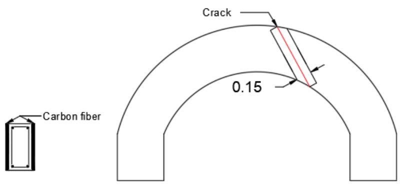


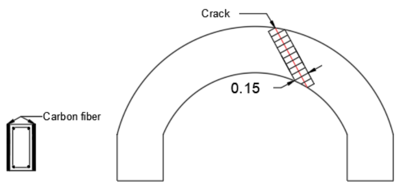
Figure 3: Preparing the Crack specimens (Ic1 and Ic2). (The drawing's dimensions are in meters)



(a)



(b)



(c)

Figure 4: The location and dimensions of the carbon fibers (the dimensions of the drawing are in meters): (a) The specimen (Hc1). (b) The specimen (Ic1). (c) The specimen (Ic2)

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The samples were prepared for testing by installing one of the "Linear Variable Differential Transducers" (LVDT) vertically in the mid-span of the specimen to record the deflection. The second (LVDT) was placed horizontally at the mid-span to measure the lateral displacement. One Point load was used for all specimens at mid-span, as shown in Figure (5). The specimens were tested using a hydraulic testing machine with a loading capacity of (50 Tons) to apply monotonic loads applied gradually with a ratio of (1.0 kN) per minute, as shown in Figure (5). A load cell was installed under the hydraulic piston to measure the amount of load applied to the arch. All parts were connected to a data logger to record all testing data transferred to the computer. A fixed support was being used to support the arch on both sides.

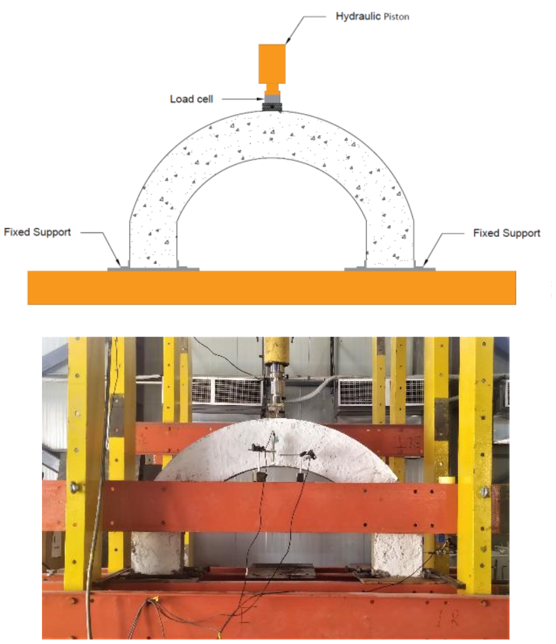

Figure 5: The loading and supporting method for the arches

V. RESULTS AND DISCUSSIONS

All results obtained from the test specimens from each step against the recorded deflection and lateral displacement are recorded and plotted. The initial cracking load and failure load were recorded. Results in terms of load and displacement for the models were compared and discussed. The shape and distribution of cracks for the specimens are shown in Figure (6). The load-deflection curves at the mid-span of the specimen are shown in Figure (7). The load-lateral displacement curves at the mid-span of the specimen are shown in Figure (8). Table (2) shows the results obtained from testing the arch beam specimens.

By testing the standard specimen (S), it was noticed that the first crack appeared at a load of ($P_{cr.}$=41kN) with a crack deflection at midspan ($\delta_{cr.}$=1.2mm). That diagonal cracks start from the bottom at the mid-span and extend upward to the applied load point. Then horizontal cracks were initiated in the bottom middle region. Diagonal cracks appeared at the top of the beam at a quarter of the beam span from both sides. The failure load was equal to ($P_{f.}$=250kN)) with a failure deflection at midspan ($\delta_{f.}$=7.15mm), and the concrete was crushed at a crushing (fracture) load of ($P_{fract.}$=320kN) with a fracture deflection at midspan ($\delta_{fract.}$=10.6mm).

Test of (Hc1) beam shows the same behavior and cracking patterns as the standard beam. The first crack was developed at load ($P_{cr.}$=38 kN) with deflection lesser than the standard beam ($\delta_{cr.}$=0.99mm). The specimen failed at a load of ($P_{f.}$=230kN) against ($\delta_{f.}$=8.93mm) and was crushed at load ($P_{fract.}$=384kN) with crushing deflection ($\delta_{fract.}$=14.79mm). Meanwhile, the Hc2 beam had a first crack load of ($P_{cr.}$=48kN) with deflection more than the standard beam ($\delta_{cr.}$=1.3mm). The specimen failed at a load of ($P_{f.}$=220kN) against ($\delta_{f.}$=7.01mm) and was crushed at load ($P_{fract.}$=396.7kN) with crushing deflection($\delta_{fract.}$=16.69mm). However, the (Hc)'s groups suffer from severe crushing at the end of the tests, as shown in Figure (6).

The (Ic)'s group showed crack patterns similar to that in the standard beam with more crack intensity at the midspan. The Ic1 beam recorded the first crack load (Pcr.=22kN) with deflection lesser than the standard beam (δcr.=0.6mm). The specimen failed at a load of ($P_{f.}$=180kN) against ($\delta_{f.}$=7.41mm) and was crushed at load ($P_{fract.}$=343kN) with crushing deflection ($d_{fract.}$=13.1mm). The Ic2 beam's first cracking load was ($P_{cr.}$=26kN) with deflection ($\delta_{cr.}$=0.8mm). The beam failed at a load ($P_{f.}$=185kN) against ($\delta_{f.}$=6.49mm) and was crushed at load ($P_{fract.}$=337.7kN) with crushing deflection ($\delta_{fract.}$=13.41mm). No severe crushing at the end of the tests was shown in this group.

It is worthwhile to mention that no cracks appeared near the supports. The column was working properly without any sign of failure for all groups. The failure in the five samples was the beam cracking and crushing cross-section at midspan due to flexural stresses.

Figure (7) shows the mid-span deflection for all groups. Comparing the values of the mid-span deflection at a load of (300 kN) showed that the lowest deflection was recorded for the standard beam (δ=10mm). The deflection increased with the increasing the resistance value of (Hc)'s group to be (δ=11.5mm) and (δ=13mm) for (Hc1) and (Hc2) beams, respectively. The deflection values were (δ=12.5mm) and (δ=12.6mm) for (Ic1 and Ic2) beams, respectively.

Figure (8) shows the lateral displacement for all groups. Comparing the values of the lateral displacement at a load of (300 kN) showed that the most significant displacement was

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recorded for the standard beam (δl=4.1mm). The displacement decreased in (Hc)'s group to (δl=3.5mm and δl=1.33mm) for (Hc1 and Hc2) beams, respectively. The values of lateral displacement were (δl=3.1mm and δl=2.8mm) for (Ic1 and Ic2) beams, respectively.

(a) Beam (S)

(b) Beam Hc1

(c) Beam Hc2

(d) Beam Ic1

(e) Beam Ic2

Figure 6: The shape and distribution of cracks for the tested beams

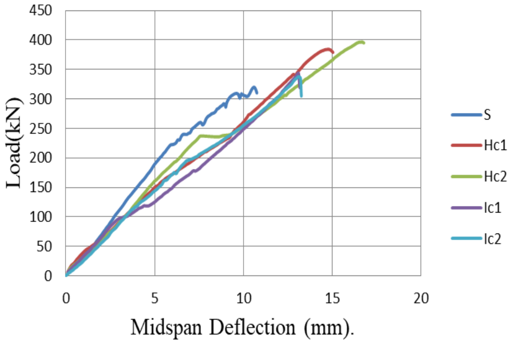

Figure 7: The relationship between the load and the deflection at the mid span of the specimens

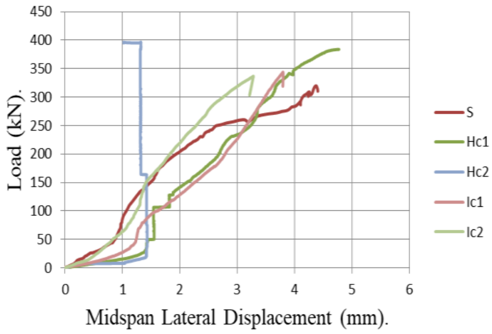

Figure 8: The load-lateral displacement relationship at mid-span of specimens

Table 2: The results obtained from testing the specimens

No.	Beam	P_{cr} (kN)	$P_{cr.}$ diff. %	$\delta_{cr.}$ (mm)	P_f (kN)	$P_{f.}$ diff. %	$\delta_{f.}$ (mm)	$P_{fract.}$ (kN)	$P_{fract.}$ diff. %	δ_{fract}(mm)
1	S	41	-	1.2	250	-	7.15	320	-	10.6
2	Hc1	38	-7.3	0.99	230	-8	8.93	384	+20	14.79
3	Hc2	48	+17.1	1.3	220	-12	7.01	396.7	+23.9	16.69
4	Ic1	22	-46.3	0.6	180	-28	7.41	343	+7.187	13.1
5	Ic2	26	-36.6	0.8	185	-26	6.49	337.7	+5.53	13.41

VI. CONCLUSION

As a result of the experimental findings, the following conclusions can be drawn:

1. Compared with the standard beam, the (Hc1) beam gives a (20%) increase in fracture load and a (39.5%) increase in fracture deflection. The Hc1 beam demonstrated an (8%) reduction in initial failure load and a (24%) increase in deflection corresponding to the failure load.
2. The strengthening method used in (Hc2) led to a (23.9%) increase in fracture load and a (57.4%) increase in fracture deflection compared with the standard beam.

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The initial failure load was also reduced by (12%), and the failure deflection was reduced by (1.96%).

3. The strengthening method utilized in beam (Hc2) increased the fracture load by (3.3%) compared to beam (Hc1).
4. Compared to standard beam (S), the strengthing of beam Ic1 increases the fracture load by about (7.19%) and the vertical fracture deflection by (23.6%). The (Ic1) beam gave a failure load of 28% lower and a deflection higher by (3.6%). It also gave a cracking load lesser by about (46.3%) and a deflection value lesser by about (50%).
5. The strengthening of the beam's (Ic2) resulted in a (5.53%) increase in fracture load, with a greater deflection of about (26.5%). The failure load value for the (Ic2) beam was (26%) lower than the standard beam, and the failure deflection was also lower by (9.23%). The cracking load also decreased by (36.6%), and the deflection decreased by about (33.3%).
6. The strengthening method utilized in beam (Ic1) increased the fracture load by (1.6%) compared to beam (Ic2).

Highlights:

- Behavior Investigation of Arch Beams Using Different Types of Strengthening Methods was conducted.
- Results of two different opening strengthening methods of arched beams were compared.
- Results of two different crack strengthening methods of arched beams were compared.
- The strengthening method utilized in beam Hc2 increased the fracture load by 3.3% compared to beam Hc1.
- The strengthening method utilized in beam Ic1 increased the fracture load by 1.6% compared to beam Ic2.

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