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Finite Element Analysis of R.C. Arches with Openings Strengthened by CFRP Laminates

AMMAR YASER ALI* AND BASHAR ABID HAMZA†

*(Professor)
College of Engineering
University of Babylon
e-mail: dr_ammaraljanabi2005@yahoo.com

†(Lecturer)
College of Engineering
University of Babylon

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Abstract. The main objective of this research is to present an analytical study to investigate the behavior and performance of reinforced concrete arches with and without openings , un-strengthened and strengthened (externally by CFRP laminates or internally by steel reinforcement) and comparison with experimental results. Twelve tested reinforced concrete semi-circular arches with and without web openings were analyzed with cross-section of (150*250mm) and inner diameter (1500mm) and outer diameter (2000mm).The variables considered in this research included: curvature forces , location of opening through profile of arch, and type of strengthening.
ANSYS computer program (version 11, 2007) was performed throughout this study. Full bond was assumed between the CFRP and concrete and between steel reinforcement and concrete. Brick elements SOLID 65 and SOLID 45 was used to represent concrete element and steel plate, respectively. While LINK8 and SHELL 41 were used to represent steel reinforcement and CFRP laminates, respectively. In general, a good agreement between the finite element and experimental results has been obtained concerning load –deflection response and mode of failure , where cracking and ultimate loads with average difference about 5.83% and 3.92%,respectively.

1 INTRODUCTION

An arch may be defined as a curved girder having convexity upwards, and supported at its ends. The main aim of arch is to enhance the load carrying capacity, which may come from the stiffening behavior due to membrane action. This characteristic enabled structural engineers to achieve large spans in buildings roofing and bridges decking using materials with efficient compressive strength, like concrete, or using suitable compression resisting systems, like braced and trussed metal structures to overcome the dominant compressive stresses generated in the arches. On the other hand, an axial force is introduced due to the arch action. This state of action is compatible with concrete materials, which is relatively weak in carrying tension and shear stresses, but adequate in carrying compressive stresses [1].

2 OPENING IN REINFORCED CONCRETE BEAMS

In the construction modern buildings, a network of pipes and ducts is necessary to accommodated essential services like water supply, sewage, air-conditioning, electricity, telephone, and computer network. Usually, these pipes and ducts are placed underneath the beam soffit and, for aesthetic reasons, are covered by a suspended ceiling, thus creating a dead space. Passing these ducts through transverse openings in the floor beams leads to a reduction in the dead space and result in a more compact design [2]. Figure 1, shows a view of the typical layout of pipes for building.

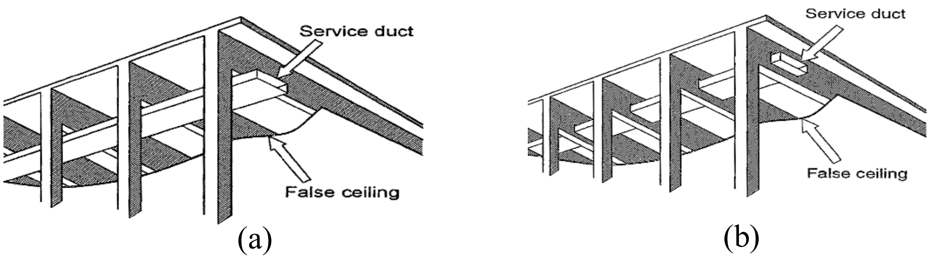


Figure 1: Typical Layout of Pipes for High Rise Building [2]
a-Typical layout of service ducts.
b- Alternative arrangement of service ducts

It is obvious that inclusion of openings in beams alters the simple beam behavior to a more complex one. Due to abrupt changes in sectional configuration, opening corners are subject to high stress concentration that may lead to cracking unacceptable from aesthetic and durability viewpoints. The reduced stiffness of the beam may also give rise to excessive deflection under service load and result in a considerable redistribution of internal forces and moments in a continuous beam. Unless special reinforcement is provided in sufficient quantity with proper detailing, the strength and serviceability of such a beam may be seriously affected [3].

3 EXPERIMENTAL WORK

The experimental program includes twelve simply supported RCsemi circular arches with and without web openings . All arches were of inner diameter 1500mm and outer diameter 2000mm, and had cross section dimensions 250mm overall depth and 150mm width. All arches were tested under two point loads at extrados (top) surface. Figure 2 shows the geometrical details of arches and the steel reinforcement provided.

The arches were divided into three groups: the first group was without opening and the other two included openings of dimensions (100*200 mm) at midspan(90^o) and at angle 45^o, respectively. Table 1 illustrates the description for each tested arch.

Table 1: Description of reinforcement and strengthening schemes of tested arches [1]

Group No.	*Arch Designation	**Location of Openings	Details			
			Web Reinforcement(Stirrups)		External CFRP Laminates	
			At Middle Sector	Around the Openings	At Middle Sector	Around the Openings
1st Group without openings	B1(Pilot)	--	--	--	--	--
	B2		Ø6@6.25°		--	
2nd Group with openings at ϴ=90° (midspan)	B3(90°)	Midspan ϴ=90°	Ø6@6.25°	--	--	--
	B4(90°-CF)			--	--	CFRP straps (2 of 40mm width on each side and 3 of 25mm width for each chord)
	B8(90°-S)			3Ø6 stirrups for each chord and 2Ø10 diagonal bars for each corner	--	--
3rd Group with openings at ϴ=45° (quarter	B5(45°)	ϴ=45°	Ø6@6.25°	--	--	--
	B6(45°-CF)			--	--	CFRP straps (1 of 75mm width on each side and 3 of 25mm width for each chord)
	B10(45°-S)			stirrups (6Ø6 for each chord and 2Ø6 full depth on each side)and 2Ø10 diagonal bars for each corner	--	--
Group without openings	B11	--	--	--	--	--
	B12				8 CFRP straps of 30mm width	

* The number inside bracket refer to position of opening. S:refers to strengthening of opening by internal stirrups.CF: refers to strengthening of opening by external CFRP laminates.
**ϴ :measured from support.

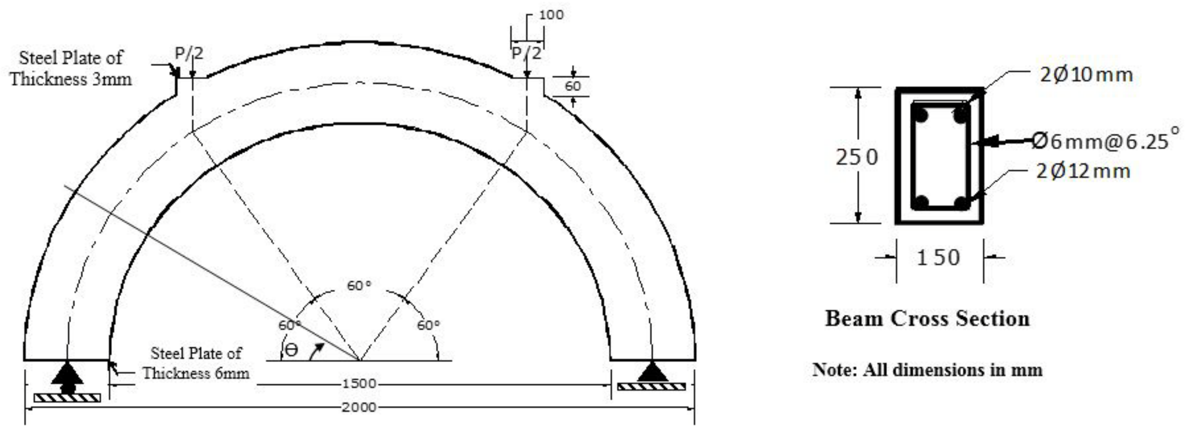


Figure 2: Geometry and reinforcement details of the tested arches

3.1 Strengthening systems

Internal and external strengthening systems were chosen carefully according to crack pattern. The method of design adopted for strengthening technique had been suggested by Mansur [4] for straight beam. The design specification of ACI 318-2011[5] and ACI Committee 440-2002 [6] was satisfied for steel reinforcement and CFRP laminates, respectively, as shown in Figure3to Figure 7 and listed in Table 1.

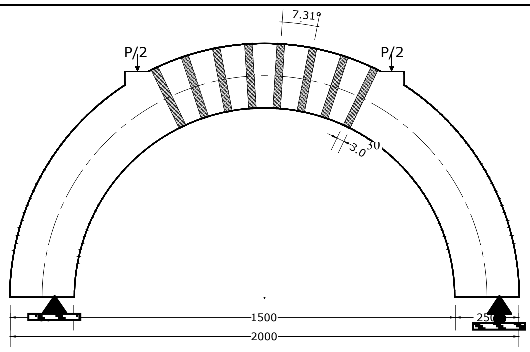


Figure 3-a: External strengthening with CFRP of arch B12

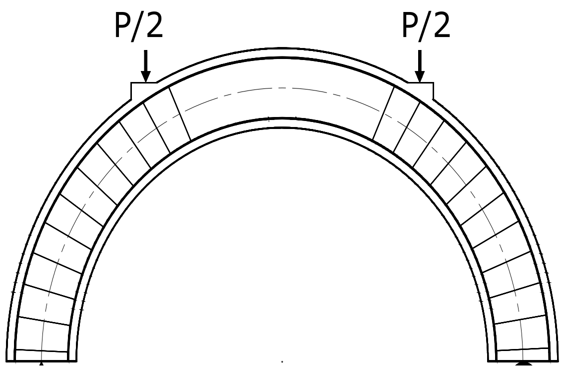


Figure 3-b: Internal reinforcements of arch B11

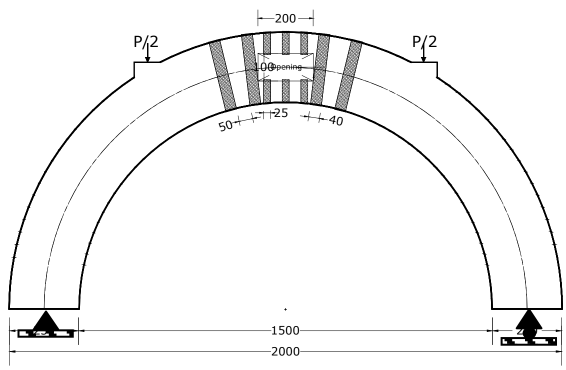


Figure 4-a: External strengthening with CFRP of arch B4(90-CF)

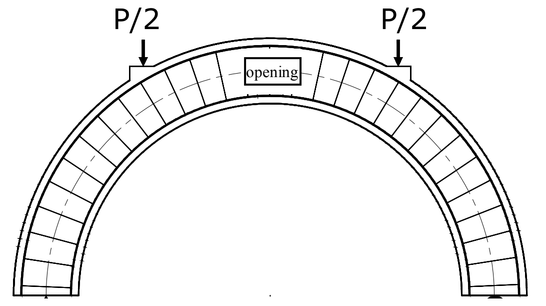


Figure 4-b: Internal reinforcements of arch B3(90)

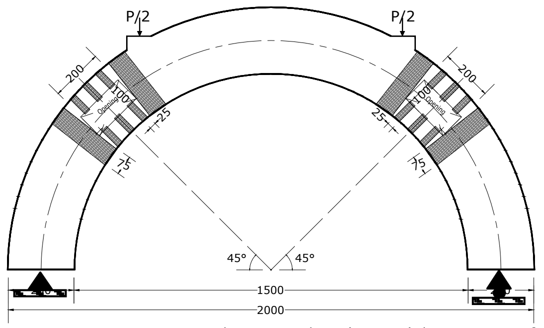


Figure 5-a: External strengthening with CFRP of arch B6(45-CF)

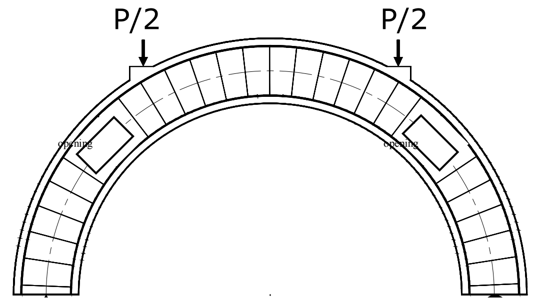


Figure 5-b: Internal reinforcements of arch B6(45)

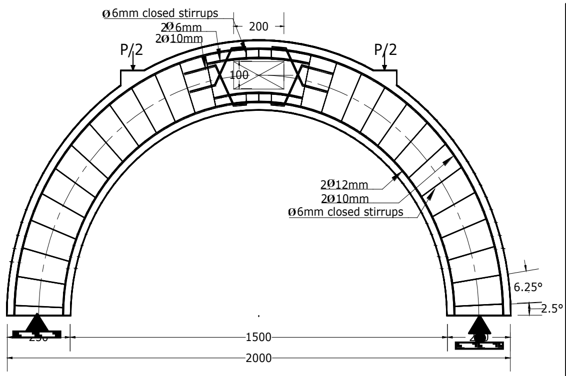


Figure 6: Internal strengthening of arch B8(90-S)

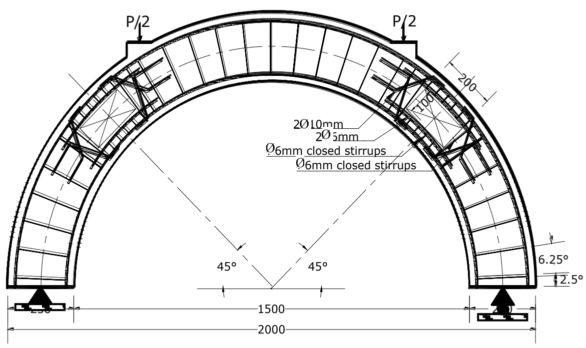


Figure 7: Internal strengthening of arch B10(45-S)

3.2 Material properties

Normal weight concrete was used to cast arches. The concrete compressive strength at time of testing (more than 28 days) are listed in Table 2. The deformed bars have (520,470 and 525) MPa yield stress for bar diameters (6, 10 and 12)mm, respectively. A CFRP sheet has a tensile strength of 4300 MPa, and modulus of elasticity of 238000 MPa, the elongation at break of 1.8% and the thickness of 0.131mm (Sika,2003) [7].

Table 2: Concrete Compressive Strength of Arches

Arch No.	B1	B2	B3(90)	B4(90-CF)	B5(45)	B6 (45-CF)	B7(15)	B8(90-S)	B9 (15-CF)	B10 (45-S)	B11	B12
Compressive strength of concrete (f'_c) (MPa)	32.8	36.5	33.3	38.34	32.0	34.2	32.4	34.1	35.61	37.4	36.1	33.0

3.3 Instrument and procedure

All of the arch beams were tested under two third point loading, with the load applied at angle 60^o from each support as shown in Figure 8. Arches were tested as simply supported (hinge-roller) in 1500 kN hydraulic testing machine at laboratory of civil engineering department of Babylon university as shown in Figure 9. A dial gage of 0.01 mm accuracy was used at the midspan of the arch and at the roller support in order to calculate the deflection and horizontal displacement of roller support, respectively.

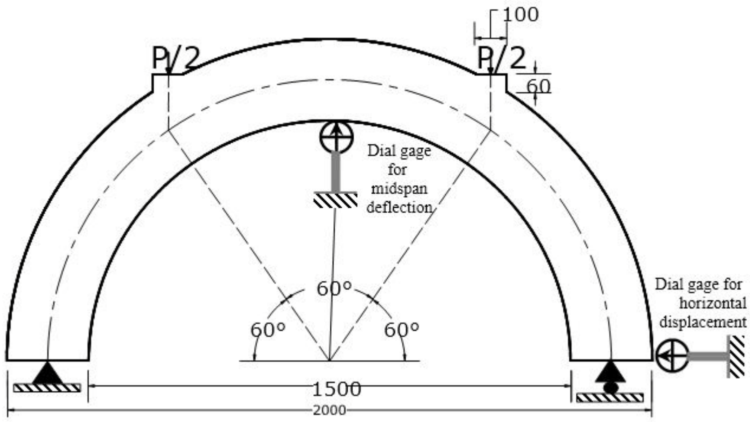


Figure 8: Loading details of test arch specimens

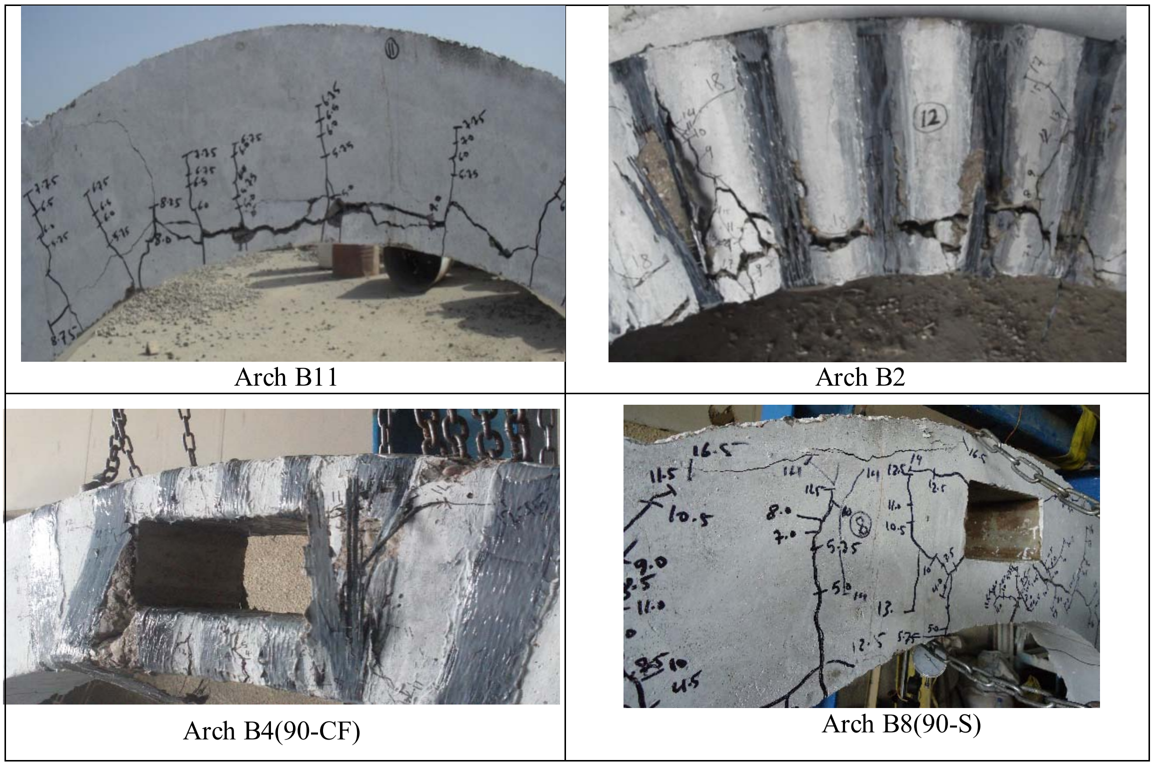
Figure 9: Loading machine used in the test

4. EXPERIMENTAL RESULTS

Table 3 and figure 10 show a summary for the test results, which include; cracking load ultimate load, ductility ration and some of failure modes. The objective was to explore the influence of internal strengthening with both stirrups and diagonal bars and external strengthening with CFRP laminates.

Table 3: Summary of experimental results of tested arches [1]

Arch		Cracking load, kN P_{cr}	Ultimate load, kN P_u	Percentage of Ultimate Load with Respect to Arch B2	Ductility Ratio	Failure Mode
Arches without Opening	Pilot(B1)	43.1	86.2	54	--	Splitting failure
	Unconfined B11	43.1	99.1	62	1.38	Splitting failure
	Internally Confined B2	38.8	159.5	--	5.9	Flexural failure
	Externally Confined B12	60.3	163.8	102.7	3.72	Rupture of CFRP
Arches with Opening at Midspan	Unstrengthened B3(90)	32.3	66.8	42	<1.0	Compression failure of top chord
	Internally Strengthened B8(90-S)	25.8	142.2	89	6.34	Flexural failure
	Externally Strengthened B4(90-CF)	34.5	133.6	83	6.72	Rupture of CFRP
Arches with Openings at angle 45°	Unstrengthened B5(45)	25.8	64.6	40	<1.0	Shear failure
	Internally Strengthened B10(45-S)	43.1	129.3	81	2.04	Shear failure
	Externally Strengthened B6(45-CF)	38.8	120.7	75	2.68	Shear failure

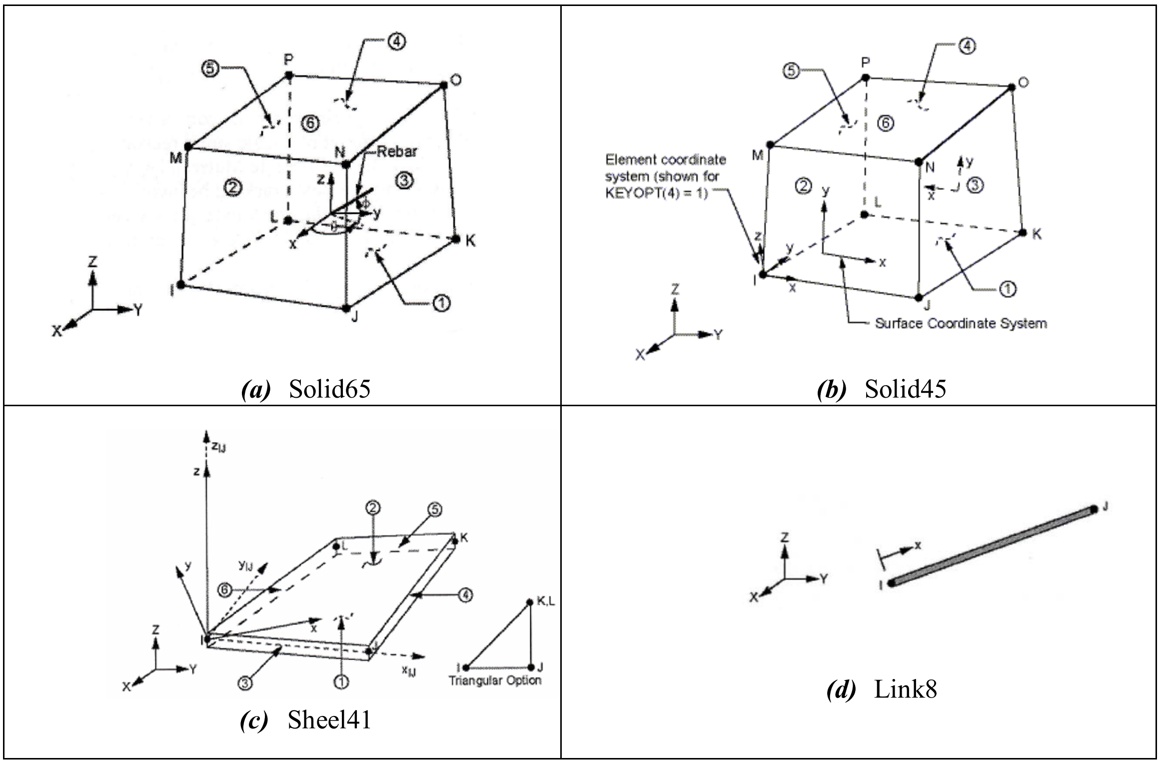


Arch B11 | Arch B2 | Arch B4(90-CF) | Arch B8(90-S)

Figure 10: Modes of fialure

5. ANALYTICAL STUDY

The analytical work included a three-dimensional nonlinear finite element model suitable for the analysis of reinforced concrete arches with or without openings and unstrengthened or strengthened by(CFRP laminates or reinforcing steel) under monotonic loading using the computer program ANSYS (Version 11.0, 2007) (8). Full bond was assumed between the CFRP and concrete surface and between the steel reinforcement and concrete. Brick element SOLID65 and SOLID45 was used to represent concrete element and loading steel plates, respectively. While LINK8 and SHEEL41 were used to represent steel reinforcement and CFRP sheets respectively. Geometry of these elements was illustrated in Figure 11 . The full Newton-Raphson Method was used for the nonlinear solution algorithm. The materials nonlinearity due to cracking, crushing of concrete, and yielding of reinforcement were taken into consideration during the analysis [8].



(a) Solid65 *(b)* Solid45 *(c)* Sheel41 *(d)* Link8

Figure 11: Geometry of elements in finite element analysis [8]

5.1 Finite element mesh (modeling)

When an increase in mesh has negligible on the results of the midspan deflection, it is assumed that the convergence of result is obtained. This convergence is found when the number of elements equals to 1392 elements for beam without opening (i.e 6, 4and 58 elements in r, z andΘ -directions) and 1984 elements for beam with opening (i.e 8, 4 and 62 elements in r, z and Θ-directions) as shown in Figure 12.

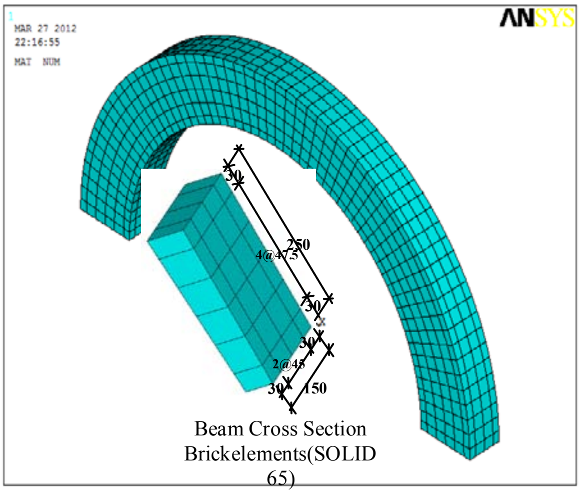


Figure 12-a: Mesh modeling of tested concrete crches

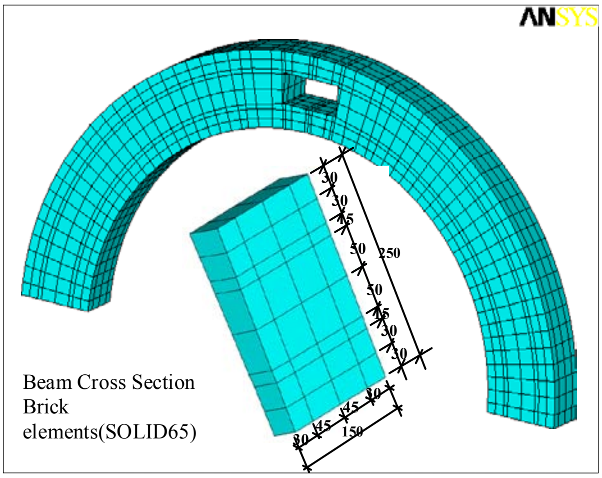


Figure 12-b: Mesh modeling of tested concrete arches with opening

5.2 Finite element results

All tested arches have been analyzed by using ANSYS computer program to determine the validity of this numerical method for the analysis of RC arches with web opening strengthened externally with CFRP laminates or internally with steel reinforcement. The results obtained from finite element analysis gave good agreement when compared with experimental results which include, cracking load, ultimate load and midspan deflection at service load as explained in Table 4.

Table 4: Comparison of Theoretical and Experimental Cracking and Ultimate Loads [1]

Arch Symbol	Cracking Load (kN)		$\frac{P_{cr)theo}}{P_{cr)exp}}$	Ultimate Load (kN)		$\frac{P_{u)theo}}{P_{u)exp}}$	Midspan Deflection at Service Load$^+$,(kN)		$\frac{\delta_{theo}}{\delta_{exp}}$
	$P_{cr)exp}$	$P_{cr)theo}$		$P_{u)exp}$	$P_{u)theo}$		δ_{exp}	δ_{theo}	
B11	43.1	36.8	0.85	99.1	111.3	1.12	4.0	2.8	0.68
B2	38.8	35.0	0.90	159.5	170	1.06	8.6	6.3	0.73
B12	60.3	40.0	0.66	163.8	170	1.04	5.2	4.5	0.86
B3(90)	32.3	32.5	1.006	66.8	70.4	1.05	2.5	2.2	0.88
B8(90-S)	25.8	25.0	0.97	142.2	142.5	1.002	10.5	6.0	0.57
B4(90-CF)	34.5	30.0	0.87	133.6	139.5	1.04	7.0	4.8	0.68
B5(45)	25.8	22.5	0.87	64.6	63.75	0.98	2.2	1.8	0.82
B10(45-S)	43.1	37.5	0.87	129.3	139.3	1.08	5.0	5.3	1.06
B6(45-CF)	38.8	39.2	1.01	120.7	123.2	1.02	4.9	4.7	0.96

+Service load =0.70$*Pu_{)exp}$

Figure 13 shows a comparison between the load-midspan deflection curves for the experimental and the numerical results. The finite element load-deflection curve for most beams showing a stiffer response rather than the experimental results because that F.E. analyses assume that concrete is a homogenous material but, the true it is a heterogeneous material as well as a perfect bond between the concrete and steel and also, between concrete and CFRP laminates is assumed in the F.E. analysis. However, the comparison shows the validity of the FEM results and the program used in application (ANSYS) by showing a reasonable agreement with the experimental results discussed previously.

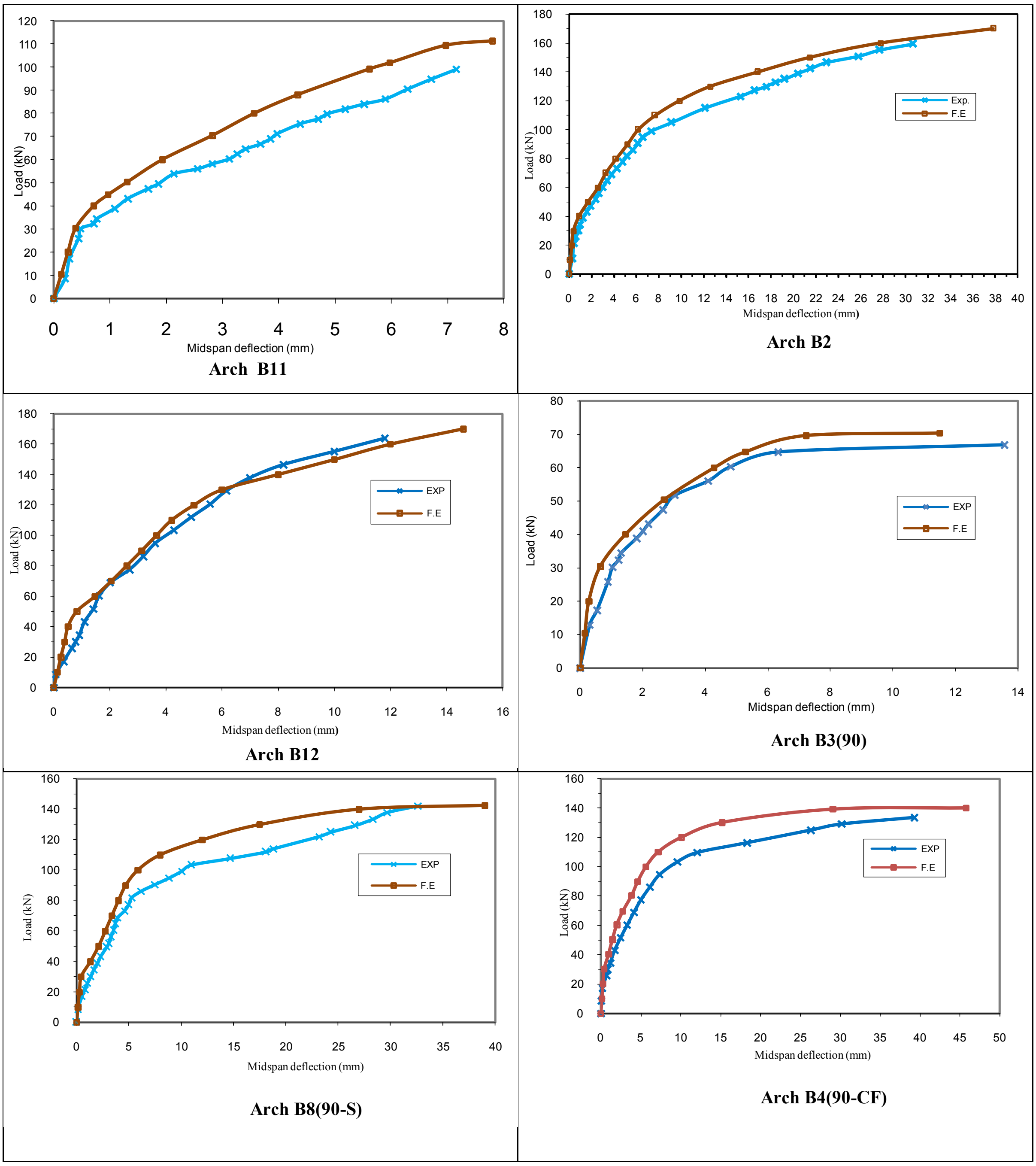


Figure 13 : Experimental and theoretical load-deflection curves for tested arches

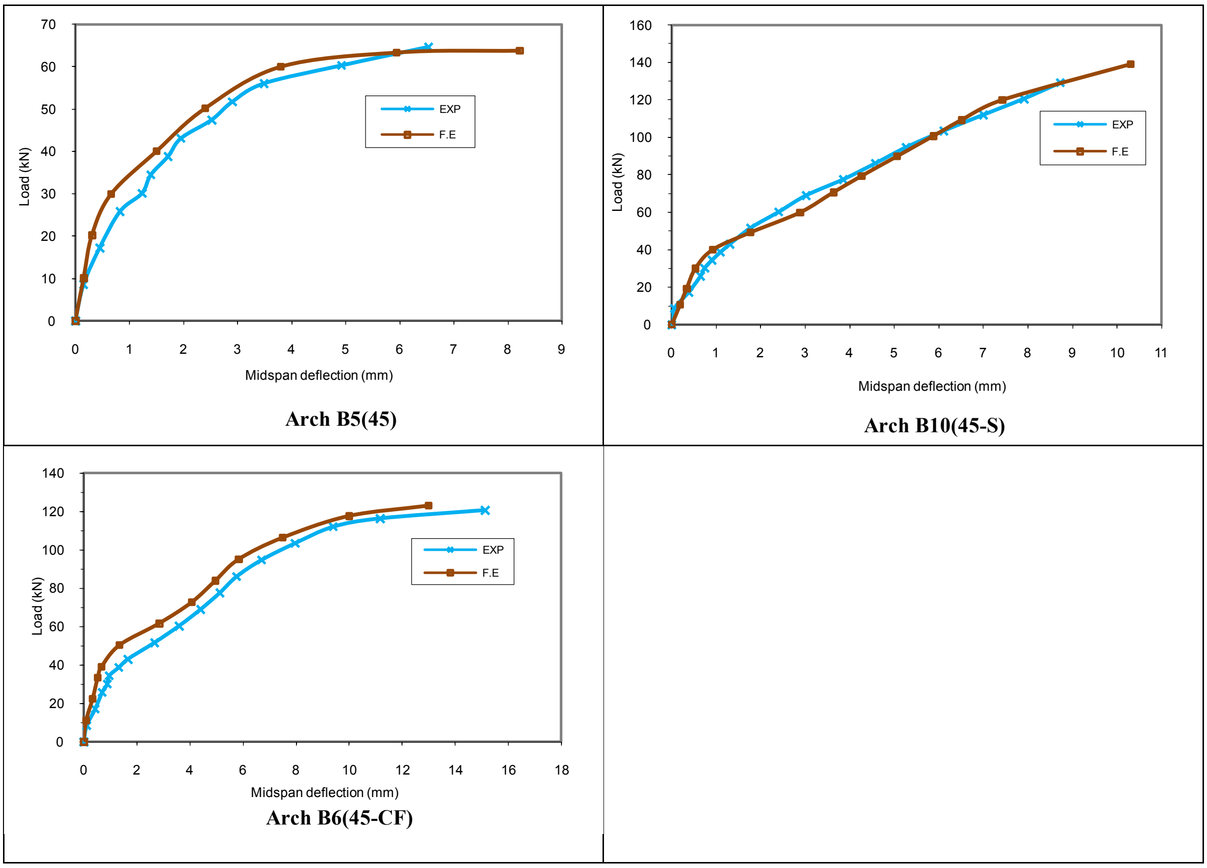


Figure 13 : Continued

6. CONCLUSIONS

- The general behavior of the finite element models which were analyzed by (ANSYS version 11.0)represented by load-midspan deflection plots showed reasonable agreement with test data plots for tested arches with maximum deviation in ultimate load of about 12%.
- The general response of externally strengthened arches by CFRP laminates was approximately in agreement with arches of internally strengthened by steel stirrups in terms of (load-deflection curves, crack pattern and ultimate loads with average difference 5.83% and 3.92%, respectively).
- In the absence of internal confining stirrups or external CFRP straps to resist curvature forces induced between reinforcing bars and concrete cover, a sudden splitting failure will occur without any warning in addition to decreasing in load carrying capacity by about 38%.
- The method of design suggested by Mansure[4] for straight beam, used herein to internally strengthening of opening at region of combined bending, shear and axial compressive forces, gave ultimate load of about 81% of solid control arch, and the mode of failure does not change (still within opening).
- The design method proposed herein for internal strengthening of opening at constant moment (pure bending) gave good result, where the mode of failure changed from failure

of opening mode to flexural failure mode. The reduction in ultimate load of strengthened arch was about 11% as compared with that of solid control arch. Also, there was an increase in the ultimate load by about 113% when compared with unstrengthened arch.

- The external strengthening by CFRP laminates enhanced the general behavior of strengthened arches in terms of (ductility ratio, mode of failure, crack pattern and ultimate load) in comparison with unstrengthened arch.
- The design method proposed herein for external strengthening with CFRP laminates of opening at pure bending region and combined of shear force, moment and axial compression force region, gave ultimate load of about 83% and 75%, respectively of solid control arch, and the mode of failure does not change (still within opening).

7. REFERENCES

(1) Bashar, A.,H.,(2013),"Behavior of RC Curved Beams with Openings and Strengthened by CFRP laminates" Ph.D. Thesis, University of Basrah.

(2) Mansur, M.A., (2006) " Design of Reinforced Concrete Beams with Web Openings " Proceeding of the 6th Asia-Pacific Structural Engongeering and Construction Conference (APSEC 2006), 5-6 September, Kuala Lumber, Malaysia.

(3) Mansur, M.A., and Hasnat A. (1979) “Concrete Beams with Small Openings under Torsion” Journal of the Structural Division, ASCE, Vol. 105, No. ST11, November, pp. 2433-2447.

(4) Mansur, M.A., (1998) “Effect of Openings on the Behavior and Strength of R/C Beams in Shear” Cement and Concrete Composites, 20, pp. 477-486.

(5) ACI Committee 318, (2011) "Building Code Requirements for Structural Concrete (ACI318M.11) and Commentary", American Concrete Institute, Farmington Hills, Michigan, USA, 473 pp.

(6) *ACI Committee 440, (2002) "Guide for the design and Construction of externally Bonded FRP Systems for Strengthening of Concrete Structures", American Concrete institute, Michigan, USA.*

(7) Sika Carbo Dur FRP Composites Construction for Repair & Strengthening of Structures . MARCH 2003 .

(8) "ANSYS Manual", Version (11.0), USA, 2007.