Nonlinear Analysis for Behavior of RC Horizontally Curved Ring Beams with Openings and Strengthened by CFRP Laminates

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ABSTRACT

This research is devoted to investigate the behavior and performance of reinforced concrete horizontally curved ring beams with and without openings, unstrengthened and strengthened (externally by CFRP laminates or internally by steel reinforcement). The experimental work consisted of fabrication and testing of four reinforced concrete ring beams. The experimental variables considered in the test program included: presence of opening in the beam, internal strengthening of the beam at the opening by reinforcing steel (stirrups) and external strengthening (confinement) by CFRP laminates for openings. The beams were tested under the action of four point loading at the top face of midspans with four supports at the bottom face of the beams. The ANSYS software was used to analyze by finite element method (FEM) both experimental specimens and theoretical ones, including the study of size and type of the openings. The results show that the presence of openings has a great effect on the behavior and ultimate load capacity of ring beams, while the strengthening of these opening by internal steel reinforcement or external CFRP laminates will increase the ultimate load capacity and affect post-cracking behavior and mode of failure of these beams. The load midspan deflection and twisting curves are shown. A comparison between experimental and theoretical results is also shown. The results computed by FEM analysis and modeling gave good agreement with experimental results.

KEYWORDS: Ring beams, Opening, CFRP Laminates, Finite element model.

INTRODUCTION

Reinforced concrete horizontally curved ring beams are used in many fields, such as in the construction of modern way intersections, circular water tanks, ring beam carrying domes, circular balconies,… etc. In the construction of modern buildings, a network of pipes and ducts is necessary to accommodate 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 will reduce the dead space and result in a more compact design.

For small buildings, the saving of dead spaces may not be significant, but for multistorey buildings, any saving in storey height multiplied by the number of stories can represent a substantial saving in total height, length of air-conditioning and electrical ducts, plumbing risers, wall and partition surfaces and the overall load on the foundation (Mansur, 2006).

A horizontally curved ring beam, loaded transversely to its plane, is subjected to torsion in addition to bending and shear. Furthermore, it is obvious that the 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 unacceptable cracking 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 (Mansur, 2006). In practice, the most common shapes of openings are circular and rectangular ones. Circular openings are required to accommodate service pipes, such as for plumbing, while rectangular openings provide the passage for air-conditioning ducts that are generally rectangular in shape.

With regard to the size of openings, many researchers use the terms ''small'' and ''large'' without any definition or clear-cut demarcation line. Mansur and Hasnat (1979) have defined small openings as those circular, square or nearly square in shape; whereas, according to Somes and Corley (1974), a circular opening may be considered as effected when its diameter exceeds 25% of the depth of the web, because the introduction of such openings reduces the strength of the beam. For small openings, two different failure modes are identified. These types of failure may be labeled as "beam-type" failure and "frame-type" failure, respectively, and require separate treatment of the complete design.

The present research aims to:

1- Investigate experimentally the behavior of reinforced concrete curved ring beams with and without openings.

2- Investigate experimentally the behavior of reinforced concrete curved beams with openings strengthened by CFRP laminates or internal reinforcement.

3- Verify the adequacy of the design method suggested for straight reinforced concrete beams with openings to utilize for the reinforced concrete curved beam with openings.

4- Carry out finite element technique to analyze the nonlinear behavior of reinforced concrete curved beams with and without openings strengthened by CFRP laminates up to failure, by using ANSYS (version 12.1) computer program.

Table 1. Descriptions of Tested Specimens

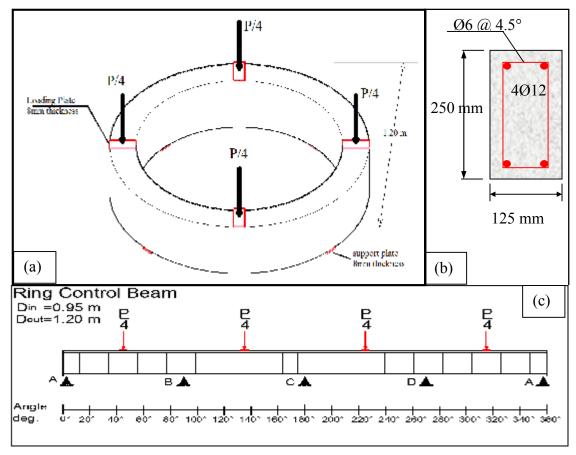| Specimen Designation	Location of Opening	Details of Reinforcement around Opening	External CFRP Laminates around Opening
FCB	---	---	---
FCB.Mo	Near Applied Load	---	---
FCB.Msr	Near Applied Load	6Ø6for each cord,2Ø6 diagonal bar for each corner, 2Ø6 at each side	--
FCB.Mcfrp	Near Applied Load	---	1of 25mm width on each side 3of 25mm for each cord

Figure (1): Details of Tested Ring Beams

a) Geometry and Load, b) Cross-Section and Reinforcement, c) Front View

Description of Specimens

All beams had an inner diameter of 950 mm and an outer diameter of 1200 mm, and had a cross-section of dimensions 250 mm overall depth and 125 mm width as shown in Fig.1. These beams were tested under the effect of four point loads located at midspan of the beam length (of angle 45°) at the top surface. Steel reinforcement was provided with a clear concrete cover to the reinforcement of 25 mm. 2 Ø12 mm deformed bars were provided for positive and negative moment regions. The closed stirrups of Ø6 mm reinforcing bar were spaced at 11° (106 mm measured at the center of the section) along the beam length. Opening dimensions are (100*200 mm) for all ring beams

except for the control beam which had no opening (solid). Table 1 illustrates details of reinforcement around opening.

Strengthening System

Strengthening system is chosen carefully according to crack pattern and failure mode. The method of design adopted for strengthening technique had been suggested by Mansur (2006) for straight beam under the effect of shear, moment and torsion. The design specification of ACI 318-2011 and ACI Committee 440-2002 was satisfied for steel bar reinforcement and CFRP laminates, respectively.

Properties of Materials

Reinforcing Steel

Two sizes of reinforcing steel bars were used in the tested beams, deformed bars of size (Ø12mm) for main longitudinal reinforcement (circumference) and deformed bars of size (Ø6 mm) for closed stirrups . Tensile test of steel reinforcement was carried out on at least three specimens, prepared for each type of the reinforcing steel bars which were used in the tested beam to determine their tensile properties according to ASTM C370-2005a. The tensile test was performed in the Central Organization for Standardization and Quality Control. The main properties are summarized in Table 2.

Table 2. Test Results of Steel Reinforcing Bars

Nominal Diameter (mm)	Measured Diameter (mm)	Yield Stress(*) f_{sy} (MPa)	Ultimate Strength f_{su} (MPa)	Modulus of Elasticity (GPa)
6	5.72	520	615	200
12	11.67	525	625	200
(*) Each value is an average of three specimens (each 40 cm of length).				

Concrete

During casting of each ring beam, three 150×150×150 mm cubes and three 100×200 mm cylinders were made. After cleaning and lubricating the molds, concrete was cast and compacted and then cured under the same conditions. Cube compressive strength and cylinder splitting tensile strength were obtained by standard tests ASTM C39-2001. The results of each ring beam are listed as average in Table 3.

Table 3. Test Results of Compressive and Tensile Strength

Beam Symbol	Compressive Strength of Concrete (MPa)(*)		Splitting Tensile Strength (f_t) (MPa)	Modulus of Elasticity Ec (MPa)(**)
	(fc)	(fc')		
FCB.P	37.13	29.70	3.4	25614
FCB.Mo	37.50	30.00	3.4	25743
FCB.Msr	41.50	33.20	3.6	27081
FCB.Mcfrp	40.38	32.30	3.6	26711

(*) $\grave{f}c = 0.8 \grave{f}cu$

(**) $(Ec = 4700 \sqrt{fc'})$

1. Carbon Fiber Polymers (CFRP)

Carbon fiber fabric SikaWrap Hex-230C and epoxy based impregnating resin Sikadur-330 were used for the technique of strengthening. The main properties of impregnating resin Sikadur-330 and carbon fiber fabric SikaWrap Hex-230C are shown in Tables 4 and 5, respectively.

Table 4. Properties of Sikadur-330 (Impregnating Resin)[(*)]

Appearance	Comp. a: white Comp. b: grey
Density	1.31 kg/l (mixed)
Mixing ratio	A : B = 4 : 1 by weight
Open time	30 min (at + 35°C)
Viscosity	Pasty, not flowable
Application temperature	+ 15°C to + 35°C (ambient and substrate)
Tensile strength	30 MPa (cured 7 days at +23°C)
Flexural E-modulus	3800 MPa (cured 7 days at +23°C)

(*) Provided by the manufacturer.

Table 5. Properties of SikaWrap Hex-230C (Carbon Fiber Fabric)[(*)]

Fiber type	High strength carbon fibers
Fiber orientation	0° (unidirectional). The fabric is equipped with special weft fibers which prevent loosening of the roving (heatset process).
Areal weight	225 g/m²
Fabric design thickness	0.131 mm (based on total area of carbon fibers)
Tensile strength of fibers	4300 MPa
Tensile modulus of fibers	238 GPa
Elongation at break	1.8 %
Fabric length/roll	≥ 45.7 m
Fabric width	305/610 mm

(*) Provided by the manufacturer.

Specimen Symbols

Figure 2 shows the casting and testing process for the ring beams. These beams were named according to the presence of opening and to the way of strengthening as follows:

FCB: Full curved beam without opening (control beam).

FCB.Mo: Full curved beam with unstrengthened opening near the applied load.

FCB.Msr: Full curved beam with strengthened opening with steel reinforcement near the applied load.

FCB.Mcfrp: Full curved beam with strengthened opening with CFRP laminates near the applied load.

Instruments and Test Procedure

Tests were carried out using 2000 kN hydraulic testing machine which was manufactured for the Civil Engineering Department of the Engineering College at Karbala University as shown in Figure 2. The main characteristics of the structural behavior of the beam specimens were detected at every stage of loading during testing. Dial gages of 0.01 mm accuracy were used at the midspan of the beam and at the outer and inner edges of the midspan section to measure the rotation at this section. The specimens were placed on the supports of the testing machine, and then the first readings of the gages were recorded. After that, the specimens were loaded with a constant rate of loading. Readings of deflection were recorded at each interval of load as well as the first crack load and the ultimate load consequently.

Figure (2): a. Specimens during Casting
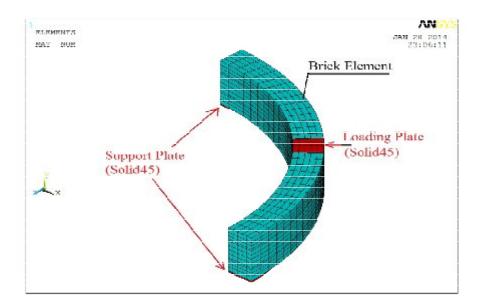**b. Specimens during Testing**

Figure (3): Adopted Description of Curved Beams (Quarter)

Finite Element Modeling

The analysis was carried out using ANSYS 12.1 program. Table 6 shows the elements used in the analysis.

Table 6. Element Types

Element No.	Element Type	Representation
1	SOLID65	Concrete
2	LINK8	Longitudinal (circumference) steel reinforcement $(\phi 12\ mm)$ and Radial reinforcement (stirrups) $(\phi 6\ mm)$
3	SOLID45	Steel plate
4	SHELL41	CFRP

The concrete was modeled with a cubic eight-node element (SOLID65) with 3 degrees of freedom in each node, and steel reinforcement was modeled as a one-dimensional element with two degrees of freedom, while (SOLID45) element was used for representing the steel support plate and (SHELL41) was used to represent the CFRP laminate, see Figure 3. A suitable mesh size was found to get the analysis results which give the best solution and the least time.

Finite Element Analysis Results

All tested curved beams have been analyzed by using ANSYS computer program to determine the validity of this numerical method for the analysis of reinforced concrete horizontally curved (ring) beams with web opening strengthened externally with CFRP laminates or internally with steel reinforcement. The overall behavior and specifications for these strengthened materials have been taken into consideration in the input data of ANSYS computer program.

The load-midspan deflection curves, load-midspan twisting angle curves, cracking and ultimate loads for all analyzed curved beams have been illustrated through the following results.

Load – Deformation Curves

Figures 4 to 7 include a comparison between the load-midspan deflection and the load-midspan twisting angle curves of the experimental and numerical results. The variations of mid-span deflection and midspan twisting angle with the step-by-step loads applied for all ring beams are all recorded through these curves. The finite element load-deflection curves for most beams show a stiffer response than the experimental results. Micro-cracks produced by drying shrinkage and handling would reduce the stiffness of the actual beam, while the F.E. does not include the effect of micro-cracks. The F.E. analysis assumes that concrete is a homogenous material, but the truth is that it is a heterogeneous material. Also, a perfect bond between the concrete and steel or CFRP laminates is assumed in the F.E. analysis.

Summary of Test Results for FCB.M Beams

Table 7 shows the cracking load, ultimate load, percentage of ultimate load with respect to FCB.P beams. Figure (8) show a comparison of load-midspan deflection and angle of twist curves for circular curved beams FCB.P, FCB.Mo, FCB.Msr and FCB.Mcfrp beams. It can be concluded that the presence of the openings near the applied load reduces the ultimate load capacity (compared with control full curved beam) to the half, also a significant reduction in twisting angle was noticed because of the ultimate load reduction. On the other hand, strengthening of the opening by internal reinforcement or external CFRP laminates increased ultimate load capacity (compared with FCB.Mo) by about 60% and 75%, respectively. Also, angle of twist and deflection were increased with considerable ratio because of the confinement of the beam at the opening region which postponed failure at opening for both types of strengthening. This is because of increasing post cracking stiffness of the beam at opening which could be seen clearly in Figure 8.
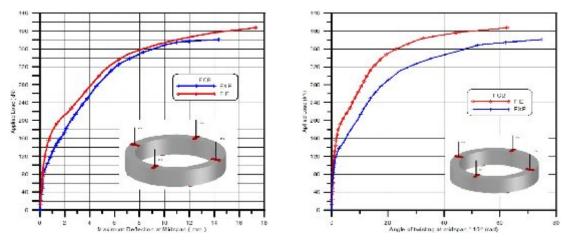
Figure (4): Load-Midspan Deflection and Rotation Curves for FCB.P Beam
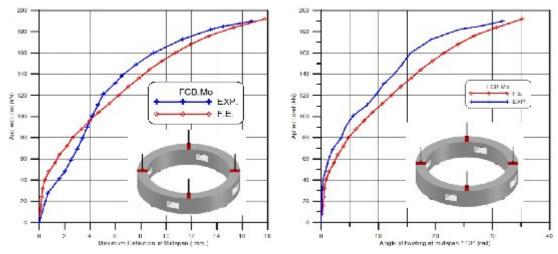

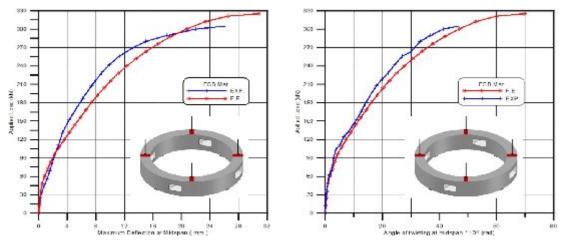**Figure (5): Load-Midspan Deflection and Rotation Curves for FCB.Mo Beam**

Figure (6): Load-Midspan Deflection and Rotation Curves for FCB.Msr Beam
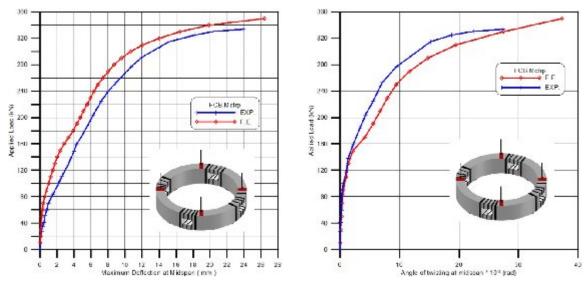
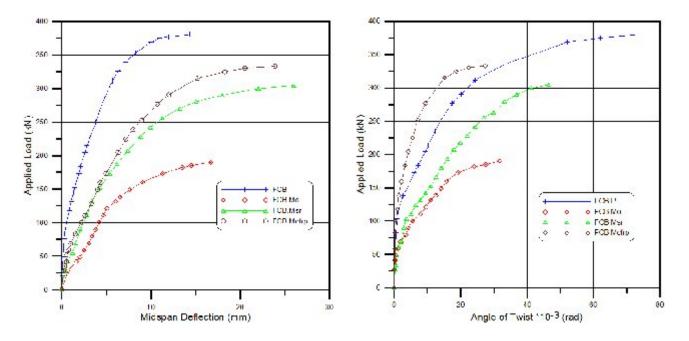**Figure (7): Load-Midspan Deflection and Rotation Curves for FCB.Mcfrp Beam**

**Figure (8): Comparison of Load-Midspan Deflection and Rotations Curves for FCB.P,
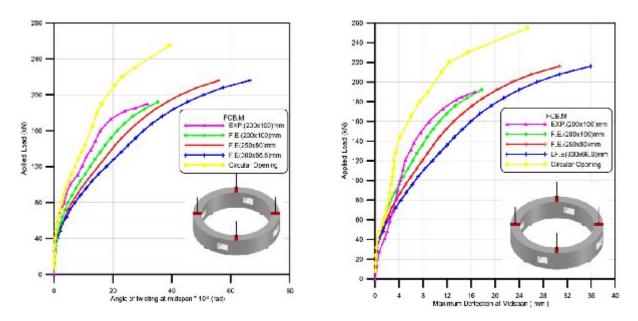FCB.Mo, FCB.Msr and FCB.Mcfrp Curved Ring Beams**

**Figure (9): Load-Midspan Deflection and Rotation Curves for FCB.Mo Circular Beams
with Different Opening Dimensions and Types**

Table 7. Summary of Tested Ring Beams							
Specimen	**Cracking Load, kN**			**Ultimate Load, kN**	*****Ultimate Load Diff. %**	**Max. $\theta \times 10^{-3}$ (rad) at midspan**	**Max. Δ at (mm) midspan**	**Failure mode**
	Corner	**Flex.**	**Tor.**					
FCB.$_P$	--	103.8	103.8	380.8	100	74.8	14.34	shear
FCB.$_{Mo}$	58.8	110.7	95	190	--	31.7	16.71	Torsional and shear
FCB.$_{Msr}$	55.4	79.8	89.9	305	60	46.4	26.04	Torsional and shear
FCB.$_{Mcfrp}$	83	100.4	128	333.5	75	27.4	23.9	Torsional and shear
Difference $= (Pu_{(\quad)} - Pu_{(\quad .\quad)})/Pu_{(\quad .\quad)}$								

Effect of Type and Size of Opening

The effect of height/length ratio of the opening on the load-deflection curve, load-angle of twist curve and ultimate load capacity of a circular curved beam with opening (FCB.Mo) was studied herein. In this study,

three aspect ratios of 1:3 (80*250), 1:2 (100*200) and 1:5 (66.67*300) were taken with constant area for all openings. A circular curved beam with circular opening of 79.8mm radius near the applied load which gives the same area of rectangular section was also

analyzed. Figure 9. shows the numerical results of the F.E. analysis with experimental results of load-deflection and load-twisting angle curves for FCB.Mo curved beams with different opening types and dimensions. It could be concluded that as the height/length ratio of the opening decreases, the load

carrying capacity increases. Furthermore, a considerable increase in load carrying capacity in beams with circular openings was found. A summary of the values of collapse loads obtained from F.E. analysis and experimental test is shown in Table 8.

Table 8. Ultimate Load Capacity for Different Opening Dimensions of FCB.Mo Curved Beams

Beam (FCB.Mo)	Opening Length (mm)	Opening Height (mm)	Ultimate Load(kN)	————
Rectangular	(Exp.)200	100	195	--
	200	100	198	1
	250	80	218	1.10
	300	66.67	218	1.10
Circular	79.8	79.8	255	1.29

CONCLUSIONS

The following conclusions were drawn from both experimental and theoretical solutions:

1. Presence of opening in circular ring beams near the applied load leads to a decrease in ultimate load capacity by about 50% when compared with the circular beam without opening (control specimen).
2. For internal strengthening of the opening region, the ultimate load capacity was enhanced by 60% and the load-deformation curve was enhanced by about 75% when compared with unstrengthened specimens.
3. The use of CFRP laminates as external confinement

in beams with opening near the applied load increased the ultimate load capacity by about 75% when compared with unstrengthened specimens.
4. A reliable enhancement appears in post-cracking behavior of specimens strengthened internally with steel reinforcement or externally with CFRP laminates.
5. The use of internal confinement changes the failure mode from beam type failure to frame type failure, while the use of CFRP laminates retains the failure mode to beam type failure.
6. The use of circular opening instead of rectangular opening with the same area increase the ultimate load capacity by about 30%.

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