Nonlinear Analysis For Behavior Of R.C. Horizontally Semicircular Curved Beams With Openings And Strengthened By CFRP Laminates

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Abstract: This research is consecrate to investigate the behavior and performance of reinforced concrete horizontally semi-circular curved beams with and without openings, unstrengthened and strengthened (externally by CFRP laminates or internally by steel reinforcement). Ten horizontally reinforced concrete semi-circular curved beams were tested in the experimental work, one without opening and nine with opening. The variables considered in the test program are: existence of opening in the beam, strengthening of the beam at the opening region internally by steel reinforcement (stirrups)and strengthening (confinement) by CFRP laminates externally for the region of openings. The beams were tested under the action of two point loads at top face of midspans with three supports at bottom face of the ends and midspan of the beams. The ANSYS software was use to analyze the finite element method (FEM) of both experimental specimens and the theoretical ones which contains the parametric study of different variables such as location of opening along the beam profile, size and type of the opening and U-strengthening using CFRP Laminates. The results shows that the presence of opening has a great effect on the behavior and ultimate load capacity of semi-circular curved 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 angle curves are shown. The comparison between the experimental and the theoretical results are also listed. The results computed by FEM analysis and modeling gave a good agreement with experimental results.

Index Terms: Semicircular beams, Opening, CFRP laminates, Finite-element model.

1 Introduction

Reinforced concrete horizontally semi-circular curved beams are used in many fields, such as in the construction of modern highway intersections, elevated freeways, the rounded corners of buildings, semicircular balconies,….etc. In the construction modern of buildings, 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 opening 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 multistory buildings, any saving in story height multiplied by the number of stories can represent a substantial saving in total height, length of air-conditioning and electrical ducts, plumbing risers, walls and partition surfaces, and overall load on the foundation [1]. A horizontally curved semi-circular curved beams, loaded transversely to its plane, is subjected to torsion in addition to bending and shear. Furthermore, it is obvious that inclusion of openings in beams alters the simple beam behavior to a more complex one.

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Due to abrupt changes in sectional configuration, opening corners are subjecting 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 momentsin 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 [2]. In practice, the most common shapes of openings are circular and rectangular. 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. The present research aims to:

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

2 Description of specimens

All beams had an inner diameter 2000 mm and outer diameter 2250 mm, and had cross section of imensions 250 mm overall depth and125 mm width as shown in Fig.(1).

These beams were tested under the effect of two point loads located at midspan of the beam length (of angle 45°) at top surface. Steel reinforcement provided with a clear concrete cover to the reinforcement of 25 mm. Two Ø12 mm deformed bars were provided for positive and negative moments regions. The closed stirrups of Ø6 mm reinforcing bar were spaced at 4.5o along the beam length. Openings dimensions are (100mm*200 mm) for all semi-circular curved beams except control beam which had no opening (solid). Table (1) illustrate details of reinforcement around opening.

Table (1) Descriptions of Tested Specimens

Specimen Designation	Location of Opening	Details of Reinforcement Around Opening	External CFRP Laminates Around Opening
SCB.P	---	---	---
SCB.Eo	Near Exterior Support	---	---
SCB.Esr	Near Exterior Support	3Ø6for each cord, 1Ø6 diagonal bar for each corner, 1Ø6 at each side	---
SCB.Ecfrp	Near Exterior Support	---	1of 20mm width on each side 3of 20mm for each cord
SCB.Mo	Near Applied Load	---	---
SCB.Msr	Near Applied Load	6Ø6for each cord, 2Ø6 diagonal bar for each corner, 2Ø6 at each side	---
SCB.Mcfrp	Near Applied Load	---	1of 25mm width on each side 3of 20mm for each cord
SCB.Io	Near Interior Support	---	---
SCB.Isr	Near Interior Support	6Ø6for each cord, 2Ø6 diagonal bar for each corner, 2Ø6 at each side	---
SCB.Icfrp	Near Interior Support	---	1of 25mm width on each side 3of 20mm for each cord
(*) definitions of symbols SCB = Semi-circular curved beam P = Control beam Ei = Exterior location of opening Mi = middle location of opening Ii= Interior location of opening		Subscript (i) denotes one of the following: o = no strengthening for opening location sr = strengthening using steel reinforcement cfrp = strengthening using cfrp laminates	

3 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[3] for straight beam under the effect of shear, moment and torsion. The design specification of ACI 318-2011[5] and ACI Committee 440-2002 [6] was satisfied for steel bars reinforcement and CFRP laminates, respectively.

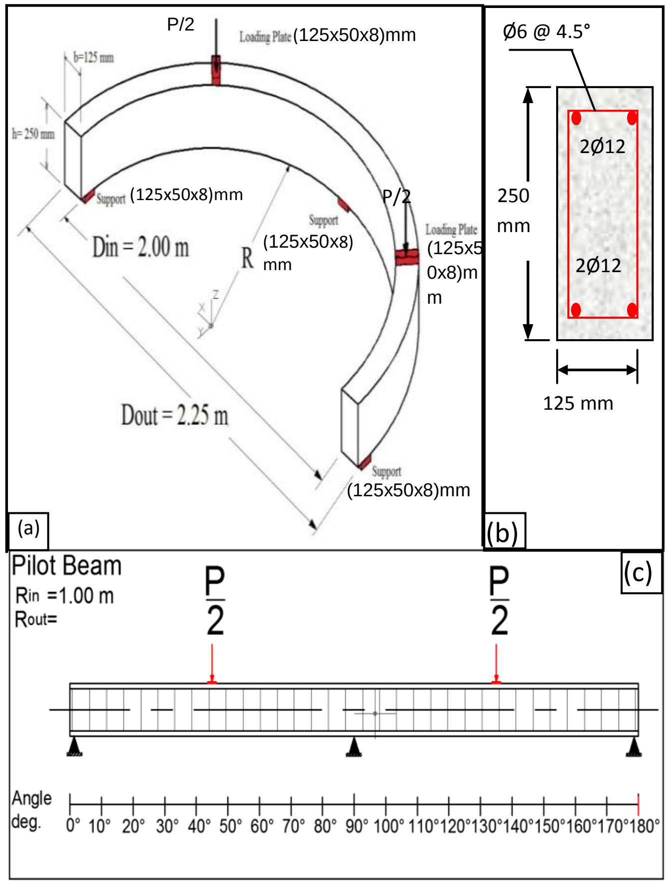


Fig.1 Details for Group I of Tested Curved Beams
a) Geometry and Load , b) Cross Section and Reinf., c) Front View

4 Specimens Symblos

Fig.(2) show 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:

SCB :semicircular beam without opening (control beam)
SCB.Eo :semicircular beam with unstrengthened opening near external support
SCB.Esr :semicircular beam with strengthened opening by steel reinforcement near external support
SCB.Ecfrp :semicircular beam with strengthened opening CFRP Laminates near external support
SCB.Mo :semicircular beam with unstrengthened opening near applied load
SCB.Msr :semicircular beam with strengthened opening by steel reinforcement near applied load
SCB.Mcfrp :semicircular beam with strengthened opening CFRP Laminates near applied load
SCB.Io :semicircular beam with unstrengthened opening near applied load
SCB.Isr :semicircular beam with strengthened opening by steel reinforcement near applied load
SCB.Icfrp :semicircular beam with strengthened opening CFRP Laminates near applied load

Fig. 2a) Specimens during casting
b) Specimens during testing

5 Finite Element Modeling

The analysis was carried out using ANSYS 12.1 Program [4]. Table (2)and Fig.(3)shows the elements used in the analysis:

Table (2): Element Types.

Elem. No.	Element Type	Representation
1	SOLID65	Concrete
2	LINK8	Longitudinal (circumference) steel reinforcement (Φ12mm) and Radial reinforcement (stirrups) (Φ6mm)
3	SOLID45	Steel plate
4	SHELL41	CFRP

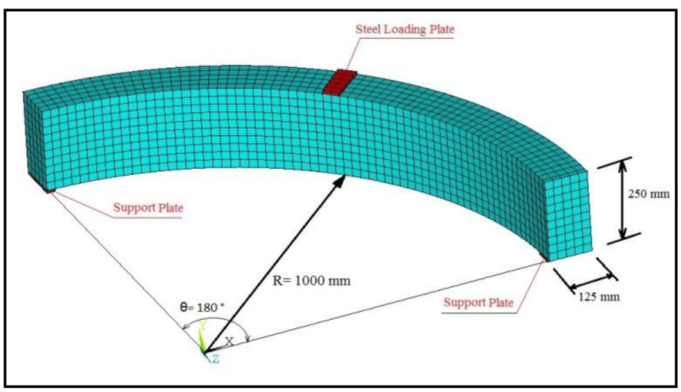
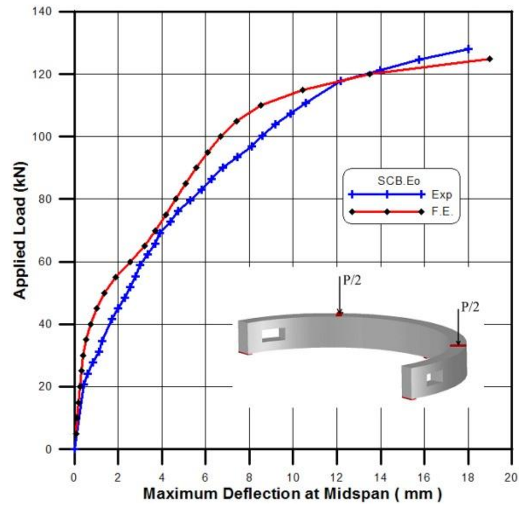
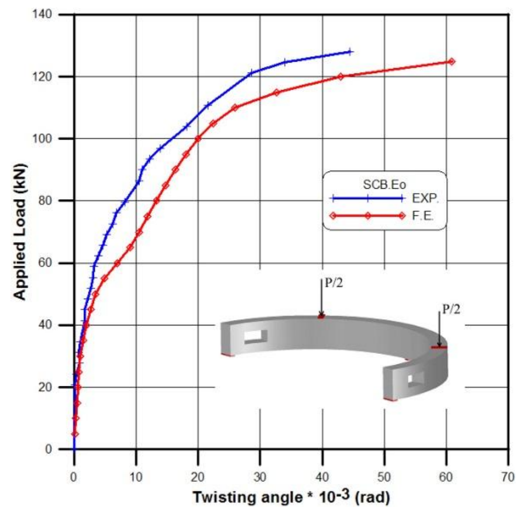


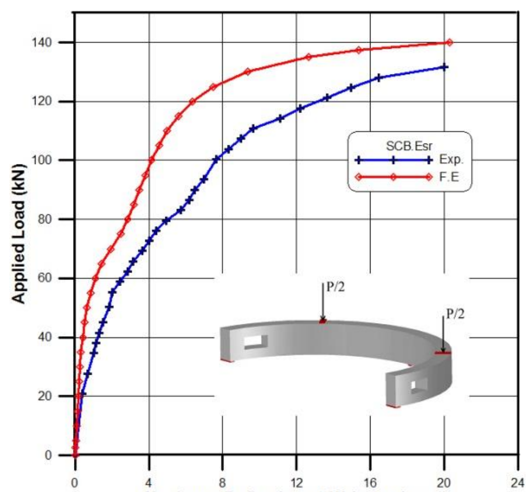
Fig.(3) Adopted Descriptions of Curved Beams (Half of Semicircular)

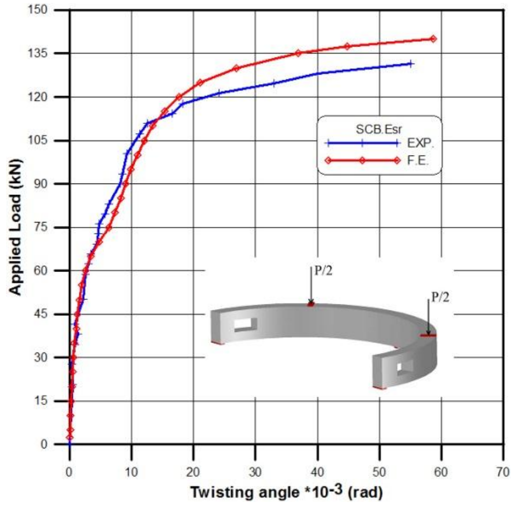
6 Finite Element Analysis Results

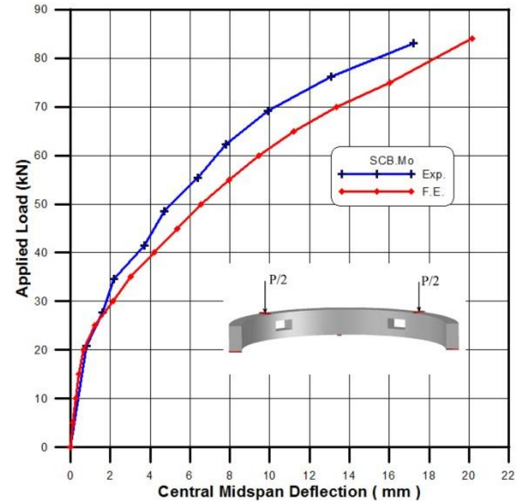
All tested curved beams have been analyzed by using ANSYS computer program to determine the validity of this numerical method for the analysis of horizontally reinforced concrete curved semicircular beams. The overall behavior and specifications for these strengthened materials have been taken in the consideration during the built up and input data of ANSYS computer program. Figs.(4) to (12) include a comparison between the load-midspan deflection and the load-midspan twisting angle curves of the experimental and the numerical results.

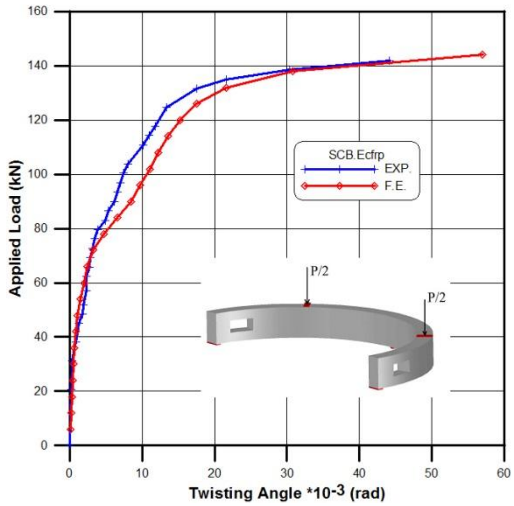


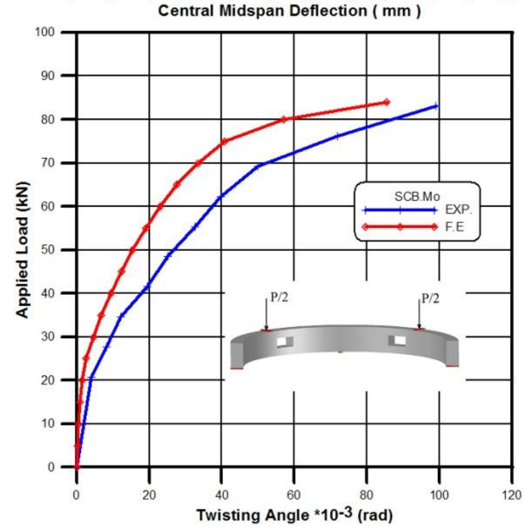


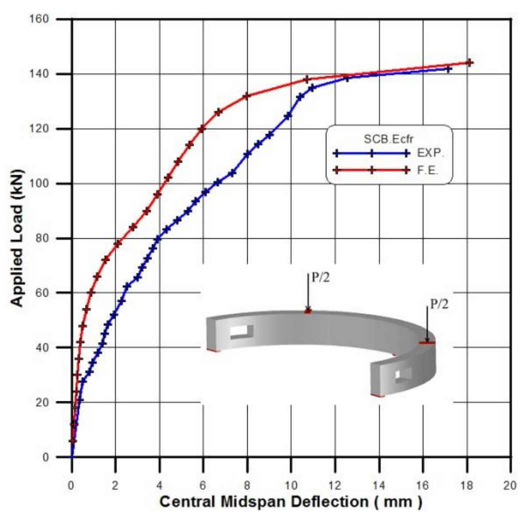


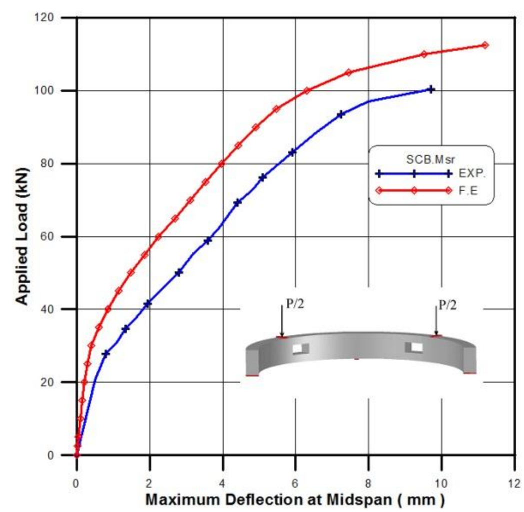

Applied Load (kN)
Twisting angle *10-3 (rad)
SCB.Esr
EXP.
F.E.
P/2
P/2

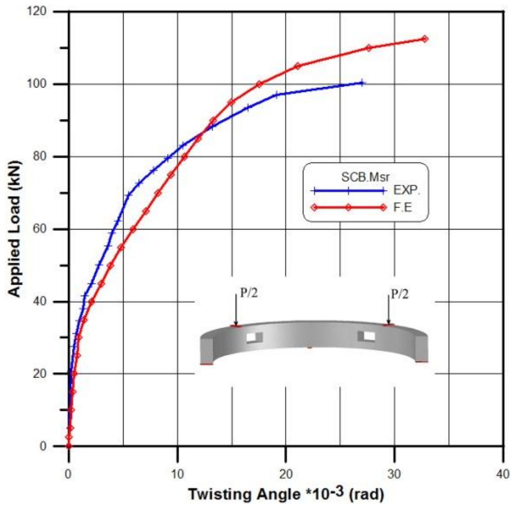

Applied Load (kN)
Central Midspan Deflection (mm)
SCB.Mo
Exp.
F.E.
P/2
P/2

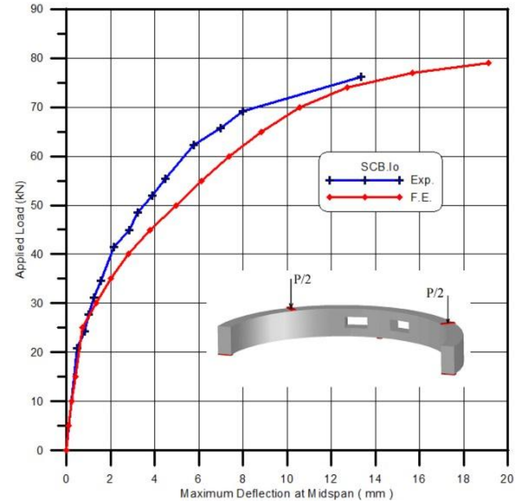

Applied Load (kN)
Twisting Angle *10-3 (rad)
SCB.Ecfrp
EXP.
F.E.
P/2
P/2

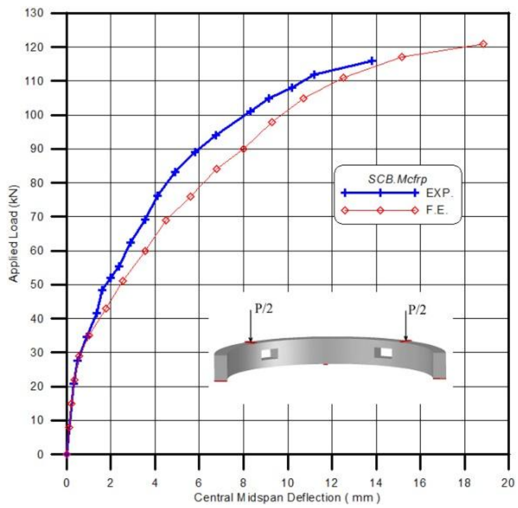

Applied Load (kN)
Twisting Angle *10-3 (rad)
SCB.Mo
EXP.
F.E
P/2
P/2

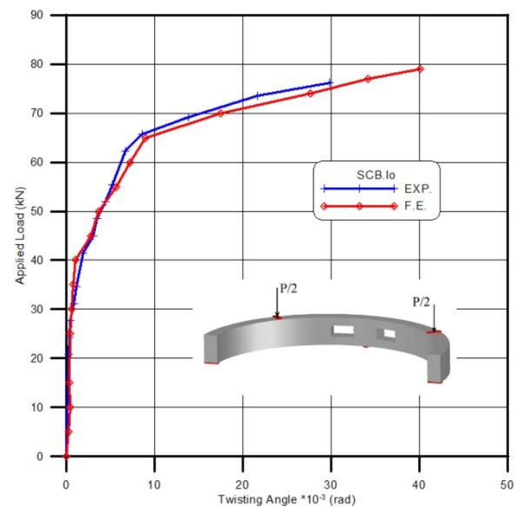

Applied Load (kN)
Central Midspan Deflection (mm)
SCB.Ecfr
EXP.
F.E.
P/2
P/2

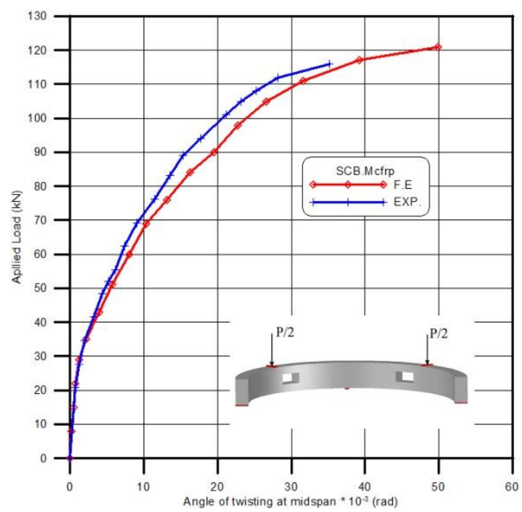

Applied Load (kN)
Maximum Deflection at Midspan (mm)
SCB.Msr
EXP.
F.E
P/2
P/2

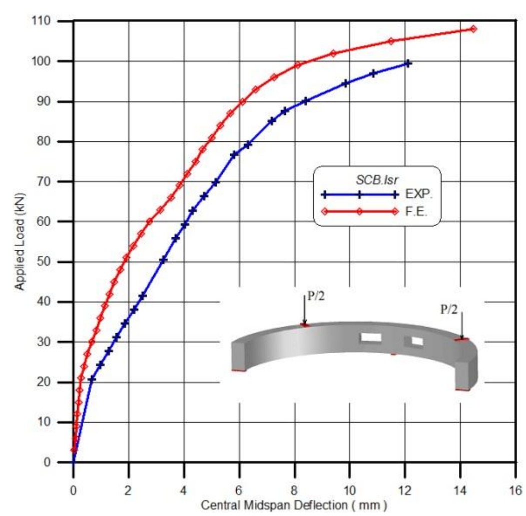

Applied Load (kN)
Twisting Angle *10-3 (rad)
SCB.Msr
EXP.
F.E
P/2
P/2

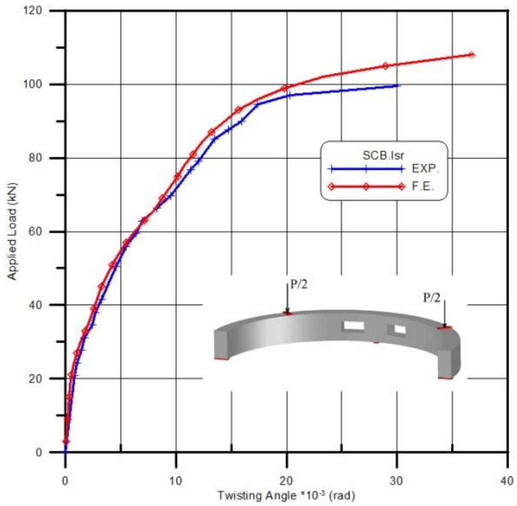

Applied Load (kN)
Maximum Deflection at Midspan (mm)
SCB.Io
Exp.
F.E.
P/2
P/2

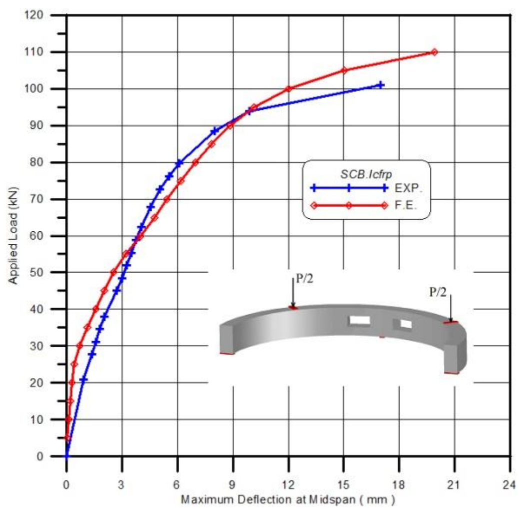

Applied Load (kN)
Central Midspan Deflection (mm)
SCB.Mcfrp
EXP.
F.E.
P/2
P/2

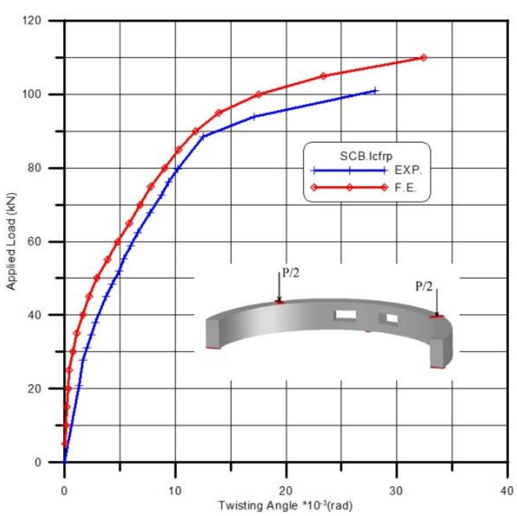

Applied Load (kN)
Twisting Angle *10-3 (rad)
SCB.Io
EXP.
F.E.
P/2
P/2


Apllied Load (kN)
Angle of twisting at midspan * 10-3 (rad)
SCB.Mcfrp
F.E
EXP.
P/2
P/2


Applied Load (kN)
Central Midspan Deflection (mm)
SCB.Isr
EXP.
F.E.
P/2
P/2







7 Summary of Test Results for Semicircular Curved Beams

Figs. (13) to (16) show a comparison of load-midspan deflection and angle of twist curves for all tested semicircular curved beams. Table (3) shows the cracking load, ultimate load, Percentage of Ultimate Load with Respect to SCB.P, percentage of strengthened spacemen to the related unstrengthened one and ratio of experimental to theoretical deflection at service load.

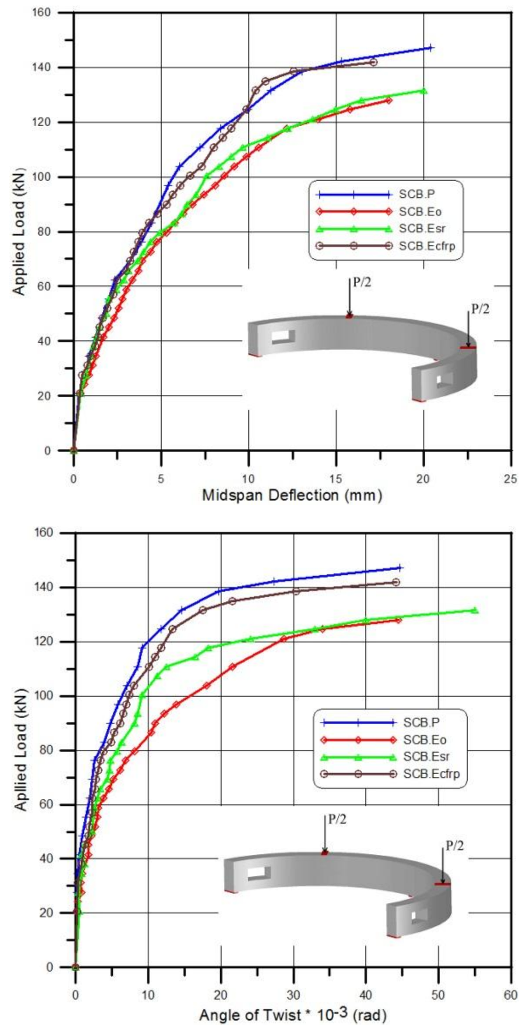


Fig13 Comparison of Load-Midspan Deflection and Twisting Curves for SCB.Ep, SCB.Eo, SCB.Esr and SCB.Ecfrp Curved Beams

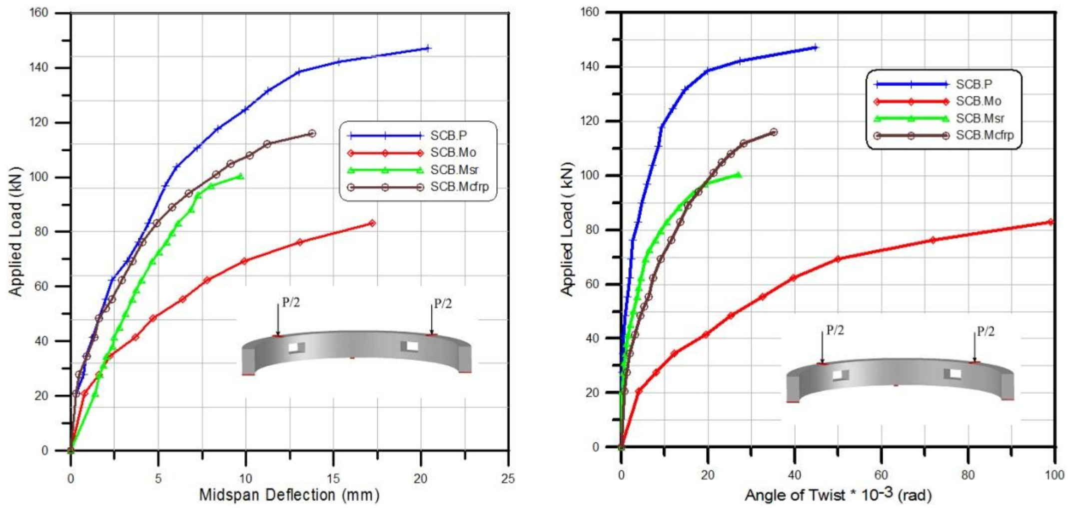


Fig. 15 Comparison of Load-Midspan Deflection and Twisting Curves for SCB.P, SCB.Mo, SCB.Msr and SCB.Mcfrp Curved Beams

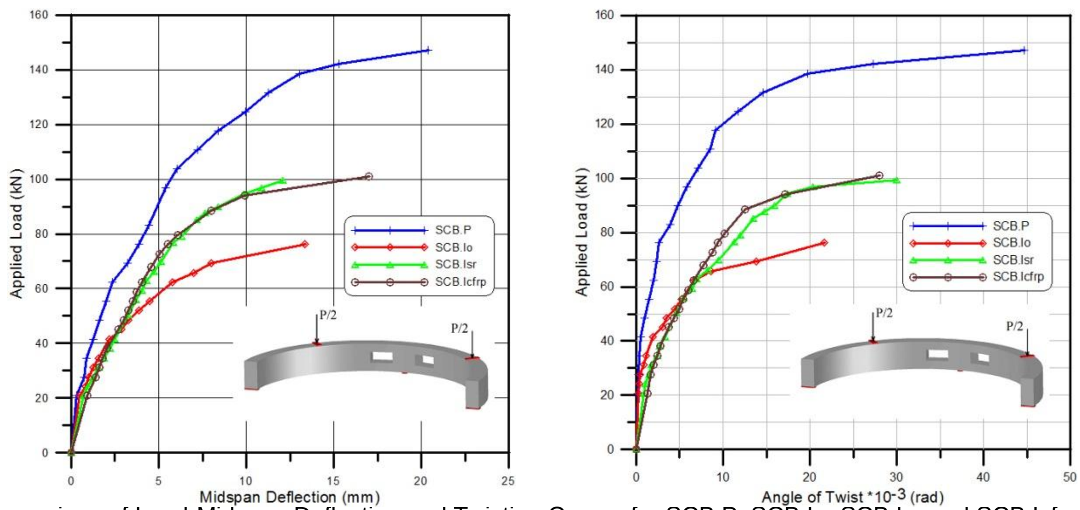


Fig. 16 Comparison of Load-Midspan Deflection and Twisting Curves for SCB.P, SCB.Io, SCB.Isr and SCB.Icfrp Curved Beams

Table (3) Theoretical and Experimental Cracking and Ultimate Loads

Beam Symbol	Cracking Load (kN)		Ultimate Load (kN)		$\frac{P_{u(exp)}}{P_{u(p)}}$	$\frac{P_{u(st)i}}{P_{u(ust)i}}$ *	$\frac{P_{u(ansys)}}{P_{u(exp)}}$	Midspan Defl. at Service Load+,(kN)		$\frac{\delta_{theo}}{\delta_{exp}}$
	Pcr)exp	Pcr)Ansys	Pu)exp	Pu)theo				δ_{exp}	δ_{theo}	
SCB.P	62.3	43.5	147.2	152.3	1.00	--	1.02	6.01	5.42	0.89
SCB.Eo	55.4	35	128.1	125	0.87	--	0.94	6.40	5.73	0.89
SCB.Esr	58.8	38.5	132.0	140	0.90	1.03	0.99	6.71	3.96	0.60
SCB.Ecfrp	72.7	45	141.9	144	0.96	1.11	0.99	6.6	4.19	0.63
SCB.Mo	34	21	83	84	0.56	--	0.89	7.15	8.89	1.24
SCB.Msr	41.5	30	100.4	112.5	0.68	1.21	0.96	4.05	3.10	0.76
SCB.Mcfrp	32	21	116	121	0.79	1.40	0.96	4.75	6.03	1.26
SCB.Io	34.6	27	76.2	79	0.52	--	0.92	4.21	5.31	1.26
SCB.Isr	41.5	33	99.5	108	0.68	1.31	0.92	5.44	3.95	0.72
SCB.Icfrp	31	25	100.9	110	0.69	1.32	0.93	4.91	5.02	1.02

+Service load =0.70*Pu) exp
*Pu(st)i= Ultimate load of strengthened spacemen
Pu(ust)i= Ultimate load of the same unstrengthened spacemen

8 Effect of Curvature

To study the effect of curvature on ultimate load capacity of horizontally curved concrete beam with openings, four types of curved R/C beams with different radius were analyzed in the present study (1m, 2m, 3m and ∞). The study carried out on semicircular curved beam with opening near interior support. The load- midspan deflection curves of all types are shown in Fig. (17). A significant difference in general response and ultimate load were noticed and recorded. An increase in ultimate load of (103%, 130%, and 172%) in curved beams of radius (2, 3 and ∞) m respectively, compared with curved beams of radius 1 m. Table (4) shows that the ultimate load for these specimens.

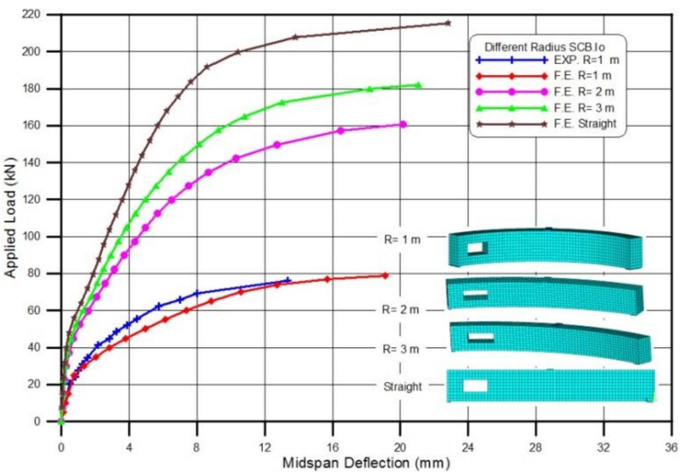


Fig. 17 Load-Midspan Deflection Curves for SCB.Io Beams With Variable Radiuses

Table (4) Ultimate Load for Different Types of SCB.Io with Variable Radiuses.

Beam radius	Ultimate Load(kN)	Increase In Ultimate Load %
Exp. R=1 m	76.16	--
F.E. R=1 m	79	--
F.E. R=2 m	160.5	103
F.E. R=3 m	182.1	130
F.E. R=∞ m	215.4	172

9 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 semicircular curved beam with interior opening (SCB.Io) was also studied here in. 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 semicircular curved beam with circular opening of radius 79.8mm at interior support which gives the same area of rectangular section was also analyzed. Fig. (18) show the numerical results of the F.E. analysis with experimental results of load-deflection and load-twisting angle curves for SCB.Io curved beam with different opening type and dimensions. It could be conclude that, as the height/length ratio of the opening decreases, the load carrying capacity increase, furthermore a considerable increasing in load carrying capacity in beam with circular opening was found. A summary of the values of collapse loads obtained from F.E. analysis and experimental test are listed in table (5).

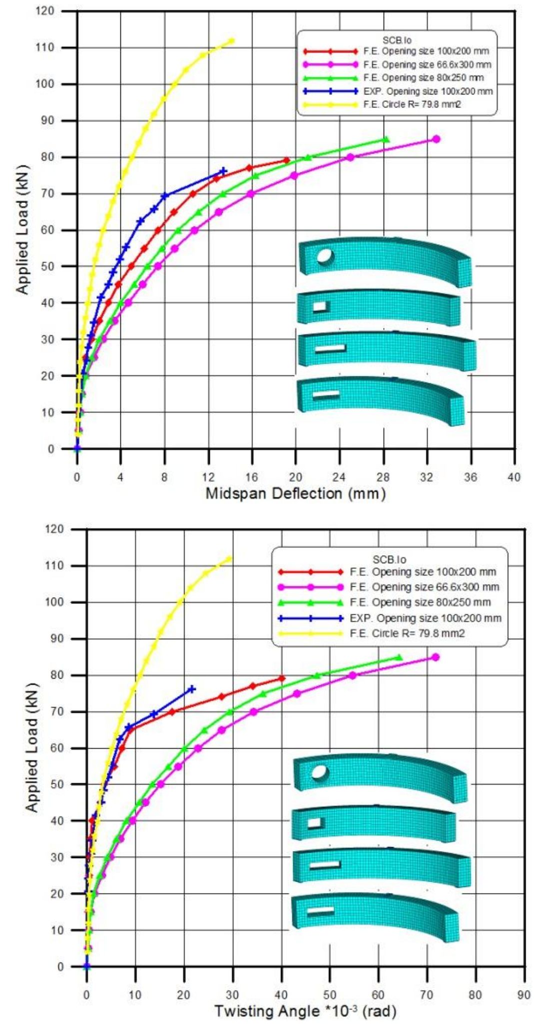


Table (5) Ultimate Load Capacity for Different Opening Dimensions of SCB.Io Curved Beam

Beam (SCB.Io)	Opening Length (mm)	Opening Height (mm)	Ultimate Load(kN)	$\frac{Pu}{Pu_{SCB.Io}}$
Rectangular	(Exp.)200	100	76.16	--
	200	100	79	1
	250	80	85	1.07
	300	66.67	85	1.07
Circular	79.8	79.8	111.8	1.41

10 Effect of Opening Length

The variation in load-deflection curve, load-angle of twist curve and ultimate load capacity of a semicircular curved beam with interior opening (SCB.Io) due to the variation of opening length were numerically carried out herein. The height of the opening was kept constant (100 mm) while its length was increased from 100 mm to 300 mm by increment of 100mm. Fig. (19) show the results of the F.E. analysis to gather with experimental results of load-deflection and load-twisting angle curves for SCB.Io curved beam. It could be noticed that decreasing in opening length leads to an increasing in ultimate load capacity of the beam. The collapse loads obtained from this study are listed in table (6).

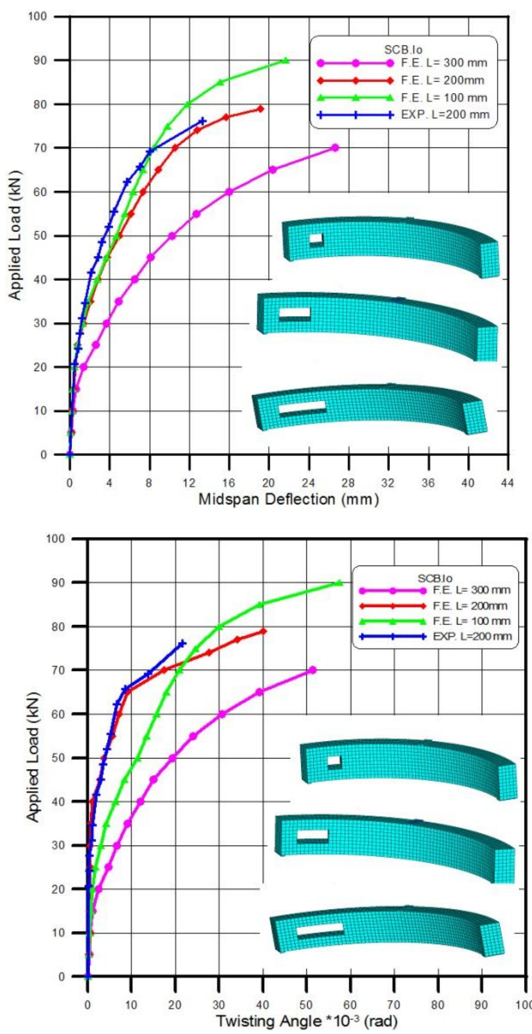


Table (6) Ultimate Load Capacity for Different Opening Length of SCB.Io Curved Beam

Opening Length (mm)	Opening Height (mm)	Ultimate Load(kN)	$\frac{Pu}{Pu_{SCB.Io}}$
(Exp.)200	100	76.16	--
100	100	90	1.14
200	100	79	1
300	100	70	0.88

11 Conclusion

The main conclusions observed from each phase of investigation (experimental program and finite element analysis) for horizontally reinforced concrete curved beam with and without openings, internally strengthened by steel reinforcement or externally strengthened by CFRP laminates are as follows:

1- The presence of opening near midspan or interior support reduced the ultimate load capacity about 35% for semi-circular beams, if compared with control beam without opening.
2- The presence of opening near exterior support of curved beam had lesser effect on ultimate load capacity, about 13% , if compared with control beam without opening.
3- The internal strengthening of the opening region by steel reinforcement (stirrups), increased the ultimate load capacity about (3% to 30%) for semi-circular curved beams, if compared with unstrengthened beams.
4- The external strengthening (confinement) of the opening region by CFRP laminates enhanced the ultimate load carrying capacity about (11% to 40%) for semi-circular curved beams, if compared with unstrengthened beams.
5- The simple method of design suggested by Mansure [3] for internally strengthening of opening region by steel reinforcement (stirrups) gave generally a good response of strengthened curved beams in terms of cracking patterns, deflection of service load as well as the mode of failure changed from mode of opening failure to beam type failure
6- The simple method of design proposed here for externally strengthening with CFRP laminates of opening region gave good result. The mode of failure changed from opening mode failure to a beam type failure.
7- The proposed simple method of design for external strengthening with CFRP laminates of the opening region, enhanced the general behavior of strengthened curved beams in terms of cracking patterns, deflection of service load as well as the mode of failure changed from mode of opening failure to beam type failure.
8- Both internal strengthened and external confinement of curved beams with opening near exterior support had a small effect on the maximum deflection and rotation (angle of twist) of midspan section at ultimate load value. While for beams with opening at midspan a decrease of (33% and 66%) occurred for deflection and rotation of midspan section. Furthermore, the deflection and rotation for beams with opening near interior support increased about 28% and 38% respectively.

9- The general response of externally strengthened specimens by CFRP laminates was approximately in agreement with specimens of internally strengthened by steel reinforcement (stirrups) in terms of deflection and ultimate loads.
10- The numerical F.E. analysis by ANSYS package is valid for the analysis of horizontally curved concrete beams with openings, unstrengthened or strengthened by internal reinforcement or CFRP laminates. The general response of load deformation curves (deflection and rotation) of F.E. analysis gave a good approchment with those of experimental curves. The comparison with experimental results confirmed the validity of the analysis with maximum deviation by about 11% in ultimate load capacity.
11- The average difference of deflections at service loads and ultimate load capacity of all specimens between theoretical and experimental results is about 4.8% and 4.1%, respectively, which insure the validity of the F.E. solution.
12- The ultimate load capacity of the curved beam with opening increased with decreasing the curvature (1/R) for the same length by about (103%,130% and 172%) for curvature (0.5,0.33 and 0.0).
13- Circular shape of opening gave an increment in ultimate load capacity about 41% more than rectangular openings.
14- Opening with length more than height for the same area gave a best ultimate load capacity than those of length less or equal height by about 7%.

References

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