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Structural Behavior of Reinforced Concrete Horizontally Curved Box Beam with Opening

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ABSTRACT

This work is dedicated to survey the structural reinforced concrete's behavior horizontally curved box beams with and without opening. Seven horizontally circular box beams were examined in the experimental work, one without opening, three with vertical opening and three with transverse opening. The test program includes the main variables; direction of opening, location of opening through profile of curved beams (effect of combination of internal forces). The beams were tested as a continuous beam with two spans, each span represents a quarter circle and under the action of two point loads each load located at top face of midspan of beam. The findings indicate that the ultimate load capacity was decreased for all specimens (CB2.V37, CB3.V60, CB4.V82, CB5.T37, CB6.T60 and CB7.T82) by about (5, 11.5, 1.5,1.5, 46.4 and 18.66%) respectively, compared to the control CB1. When compared with the control specimen CB1, all specimens were indicating an increase in Service deformations in terms of deflection and twisting angle at midspan of the circular beams. The ductility was deteriorated for all specimens with opening (CB2.V37, CB3.V60, CB4.V82, CB5.T37, CB6.T60 and CB7.T82), as a percent was about (13.88, 15.3, 19.62, 0.5, 0.5 and 13.88%) respectively, compared with that of control specimen CB1. As a result, generally, a clear degradation with different percentages in overall structural behavior of box beams horizontally curved containing opening according to the location and direction of openings, in this study the transverse openings at 60°, where the opening under the combined maximum (shear and torsion) was led to a catastrophic decrease in the structural performance of horizontally curved box beam.

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1. INTRODUCTION

Due to its structural efficiency, improved stability, serviceability, construction economy, and attractive aesthetics, box girders have achieved widespread popularity in highway and bridge systems [1]. These hollow sections are utilized to convey electrical and mechanical services while also lowering story height and construction costs. Many studies including experimental, theoretical and numerical investigations on the behavior of box beams have mainly concentrated on straight, single or multi-cell box girders, developing of numerical methods for analysis to evaluate the nonlinear response, collapse manner, and ultimate failure loads of multi-cell RC (reinforced concrete) box girder bridges under gradually rising static loads, a comparison of experimental and computational analyses was carried out [2–6].

It is becoming more usual to use horizontally curved beams for urban interchanges or highway bridges, therefore it is required to build structures that are curved in plan. The curved beams shape can be circular, elliptical, or parabolic, and it's occasionally made up of circular arcs of various radii r/and centers [7]. Many experimental investigations have looked into the structural behavior of curved beams that are loaded transversely to their plane and are exposed to torsion as well as bending and shear [8–15].

The most frequent shapes of openings in practice are circular and rectangular. Service pipes, such as plumbing, require circular apertures, but air-conditioning ducts, which are typically rectangular, require rectangular

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openings. rectangular in shape. In regards to the presence of openings in the straight solid beams only, many researchers were concentrated on its structural behavior including deformations and stiffness, collapse mechanism, as well as classifying the size of openings as small or large openings, location of openings and its effect on the beam where subjected to flexural moment, shear and torsion either individually or in combination, also effect of shape of openings was studied [16–36]. Only one experimental study including horizontally curved solid beam with openings have been conducted [37]. It can be concluded from the above that there is no research on box beams with openings and horizontally curved.

Box beams may carry a variety of cables and ducts for services such as water supply, sewage, air conditioning, electricity, telephone, and computer network, may necessitate an opening in web or flange to reach and maintain those wires and ducts. Structural behavior of box beam curved in a plane with an opening in the transverse or vertical direction has not been thoroughly investigated, so the aim of this research is to:

1. Evaluate the structural response experimentally in terms of midspan deflection and midspan-twisting of horizontally curved box beams made of reinforced concrete with and without openings.
2. Examined experimentally variation in the mode of failure of reinforced concrete horizontally curved box beams with and without opening.
3. Investigate the influence of the presence of opening on ductility and stiffness criteria of reinforced concrete horizontally curved box beams.

2. EXPERIMENTAL PROGRAM

2. 1. Material Properties

2. 1. 1. Concrete Self-Compacting concrete was selected for casting the samples due to narrow spaces and difficult geometry of box section. The mix proportions were designed by trial and error in accordance with the European Guidelines for Self-Compacting Concrete (**EFNARC**) as proposed in literature [38] with a water/cement ratio of 0.43 by weight as shown in Table 1. Ordinary Portland cement (Type I) commercially available was utilized to cast all of the specimens throughout this research. Finely ground limestone powder, having calcium carbonate ($CaCO_3$) as its main component was utilized. The maximum size of rounded coarse aggregate and fine aggregate used in the current study were (12.5 and 4.75) mm respectively. A high range water reducing agent **(HRWRA)** superplasticizer made by sika company called **Sika ViscoCrete -5930-L** which meets **ASTM C-494** Types **A** and **F** used in this work. Following standard tests, the compressive and splitting tensile strengths of concrete were found as average 40 and 3.6 MPa, respectively.

2. 1. 2. Steel Reinforcement Three different sizes of deformed bars (Ø12, Ø10 and Ø8) were used, (Ø12mm, Ø10mm) for longitudinal reinforcement (circumference) and deformed bars of size (Ø8mm) for closed stirrups. The steel reinforcement was assessed in accordance with to ASTM-A615/A-615M-05a. The yield stress of sizes (Ø12, Ø10 and Ø8) were (560, 520 and 460 MPa) respectively.

2. 2. Description of Specimens Table 2, shows circular beam specimens CB1- CB7.T82 designation. Seven semi-circular continuous curved box beams were

TABLE 1. Mix proportion of self-compacting concrete (kg/m^3)

Materials	Proportions of mix
Cement	350
Limestone powder	100
Coarse aggregate	830
Fine aggregate	830
Water	150.5
Superplasticizer	8

TABLE 2. Designation and details of tested circular beam specimens

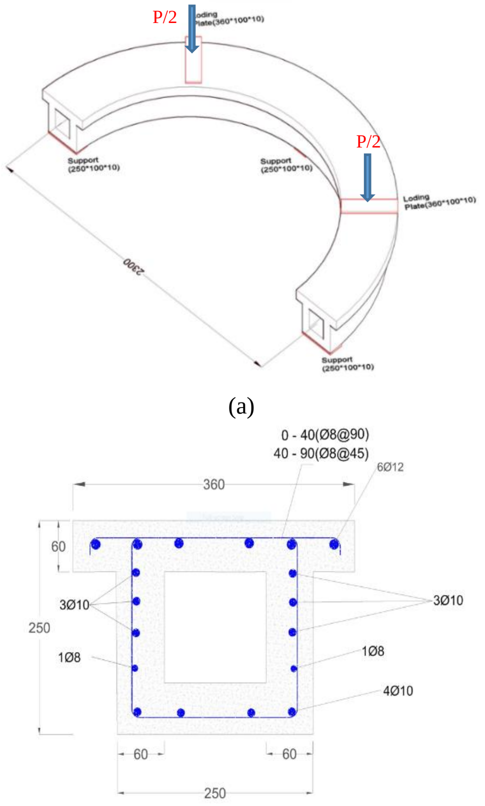
Specimen designation	Direction of opening	Location of opening	Effect of internal force at opening
CB1	---	---	---
CB2.V37	Vertical	37°	Moderate (shear, moment and torsion)
CB3.V60	Vertical	60°	Maximum (shear and torsion)
CB4.V82	Vertical	82°	Maximum (shear and moment)
CB5.T37	Transverse	37°	Moderate (shear, moment and torsion)
CB6.T60	Transverse	60°	Maximum (shear and torsion)
CB7.T82	Transverse	82°	Maximum (shear and moment)

designed in accordance with (ACI 318-19), (ACI 314R-16) and dimensions obeys AASHTO LRFD Bridge Design Specifications [39–41], consisting of two spans with hinged supports at both ends and a roller at the middle support, has a radius 1150 mm measured to the center line of cross section of the box beam as illustrated in Figure 1(a), and having cross section of dimensions 250 mm overall depth and 250 mm width with a top flange width 360mm, see Figure 1(b). The cross section of the beam includes hole with dimensions (130×130) mm to represent a box beam along the beam length, as shown in Figure 1(b). The ends of all beams extended 50 mm beyond the support's centerlines. These beams were subjected to two-point loads at the middle of each span (angle 45°). Steel reinforcement (6Ø12) mm deformed bars were provided for top negative moment regions, (4Ø10) mm for bottom positive moment regions and (6Ø10+2 Ø8) mm as longitudinal torsion reinforcement with clear cover of 20 mm. The closed stirrups of Ø8 mm reinforcing bar were placed at 90mm center to center from angle (0) to angle (40°), and placed at 45mm center to center from angle (40°) to angle (90°) along the beam length for each span, noting that the angle measured from exterior support toward the interior support. Six beam specimens had openings with dimensions of (80*80 mm), Figures 1 and 2 show the details of cut of obstruction rebars at vertical opening of specimens (CB2.V37-CB4.V82) and details of cut of obstruction rebars at transverse opening of specimens (CB5.T37-CB7.T82), respectively, while the control beam was manufactured without opening. The location of opening through each span of beam was marked by angle measured from exterior support to the center of opening. The details of cut of obstruction rebars at opening of specimens are shown in Figure 3.

2. 3. Test Setup and Procedure

Figure 4 shows the Test setup, including supporting, loading conditions and instruments. All specimens were setup inside testing machine which has a capacity of (2000 kN). The supporting system was hinged at exterior ends and roller at the inner support. Four linear variable differential transformers (LVDTs) of (0.01mm precision, 100mm maximum capacity) to measure vertical deflection and twisting at midspan, two LVDTs one localized at exterior edge and the other at interior edge for each span of beam, see Figure 4 (a-c).

As load protocol, each specimen was subjected to monotonic load was applied gradually until failure, under two-point loading, each load applied at midspan of each panel of test specimen.



(a)

(b)

Figure 1. (a) Geometry and loading of all specimens (b) Cross section and reinforcement (all units in millimeters)

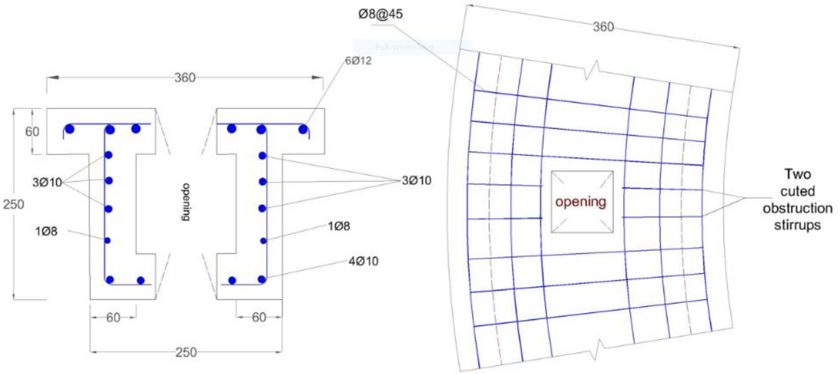


Figure 2. Details of cut of obstruction rebars at opening of specimens (CB2.V37- CB4.V82) (all units in millimeters)

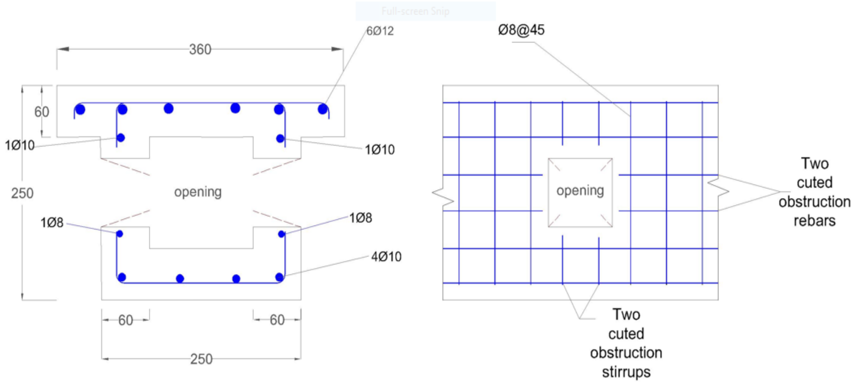
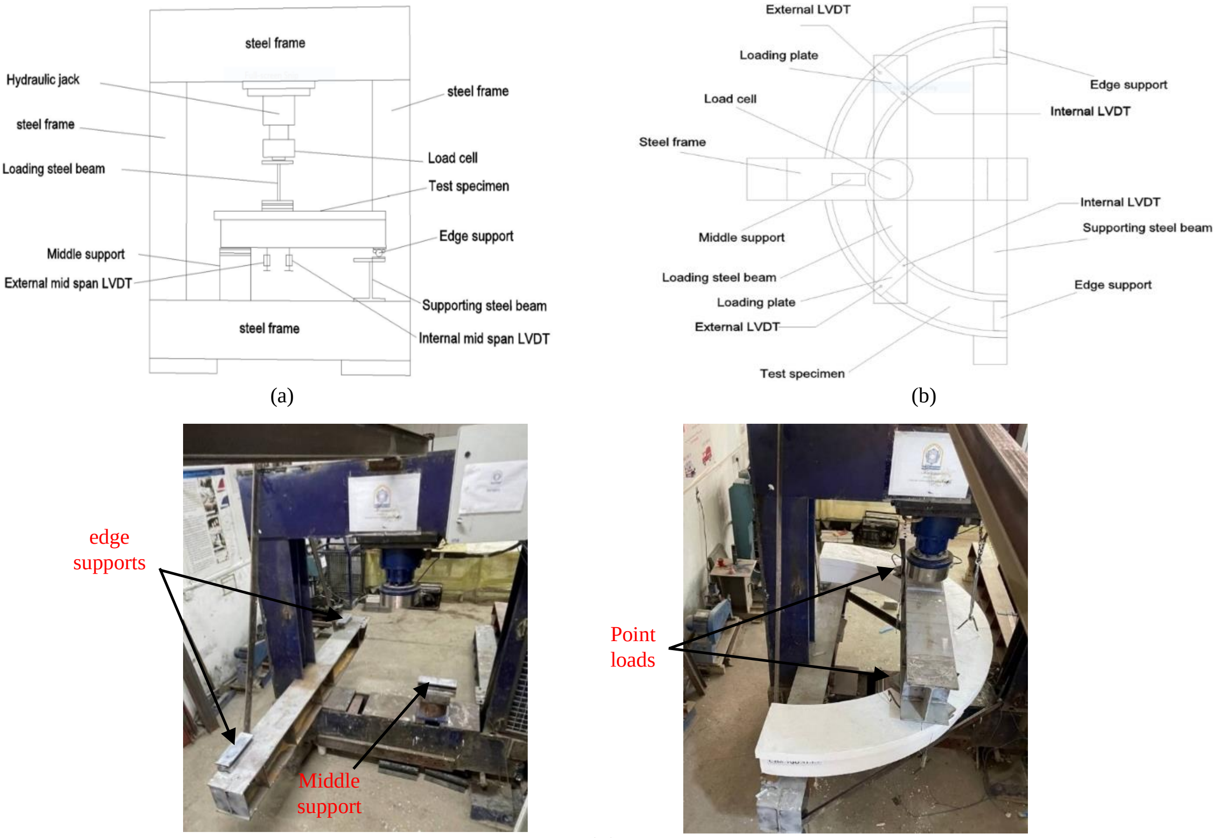


Figure 3. Details of cut of obstruction rebars at opening of specimens (CB5.T37- CB7.T82) (all units in millimeters)



(a) (b)

(C)

Figure 4. Test setup layout (a) Side view schematic drawing (b) Top view schematic drawing (c) photos

3. EXPERIMENTAL RESULTS AND DISCUSSION

3. 1. Crack Pattern and Failure Modes

The control specimen CB1 failed in a torsional-shear manner. At a load of around 50 kN, the first flexural crack was seen on the top face of highest negative moment (internal support). As the load was increased further, several flexural cracks observed at top face near internal support, at bottom face near midspan, and torsional-shear in the zones between the internal support and the loading points, Figure 5(a) shows a photograph of the specimen after failure. The ultimate load of specimen CB1 was measured 407.25 kN.

Figure 5(b) represent the photograph of specimen CB2.V37 after failure. While, the diagonal crack was appeared in one corner of lower vertical opening at load of 50 kN, no considerable change in Crack pattern and failure modes of specimen CB2.V37, which includes vertical opening between the applied load and exterior support spaced at distance d/2=125 mm from the applied load (37° measured from exterior support to the center of opening) by compare with control specimen CB1. It can be inferred that the existence of vertical openings at a 37° angle lowers the ultimate load capacity by roughly 5% (relative to the control beam), which was 385.74 kN.

Figure 5(c) represent the photograph of specimen CB3.V60 after failure, this specimen includes vertical opening positioned exactly at angle 60° measured from exterior support to the center of opening (in zone between the applied loads and internal support). Firstly, the flexural and diagonal cracks of specimen CB3.V60 were spread in a manner similar to control specimen CB1. The first visible inclined cracks at the corners of lower and upper vertical openings at load 90 kN were created. The increasing of applied load was accompanied by rapid propagation of diagonal cracks at the corners of lower vertical opening, causing frame type failure mode at vertical opening. It can be noted, that the presence of vertical openings at an angle (60°) diminish the ultimate load capacity by roughly 11.5% (when compared to control beam CB1) with maximum ultimate load capacity was about 360.3 kN.

Figure 5(d) shows the photograph of specimen CB4.V82 after failure, which includes vertical opening spaced at distance d/2=125 mm from face of internal support (82° measured from exterior support to the center of opening). The mode of failure of specimen CB4.V82 was torsional-shear, analogous to failure mode of control specimen CB1. Furthermore, all types of cracks were behaving in a mode similar to that of control specimen CB1. The ultimate load of beam CB4.V82 was measured 400.55 kN by forming large oblique torsional-shear cracks in zones between interior support and points of loading, caused very slit reduction in the ultimate load capacity (compared with control beam) was about 1.5%. Figure 5(e) shows the photograph of specimen CB5.T37 after failure. Specimen CB5.T37 includes transverse opening between the applied load and exterior support spaced at distance d/2=125 mm from the applied load (37° measured from exterior support to the center of opening). The diagonal crack was appeared in lower corner of transverse opening at load of 85 kN. Slight effect of presence of opening on the ultimate load capacity of Specimen CB5.T37 compared with control

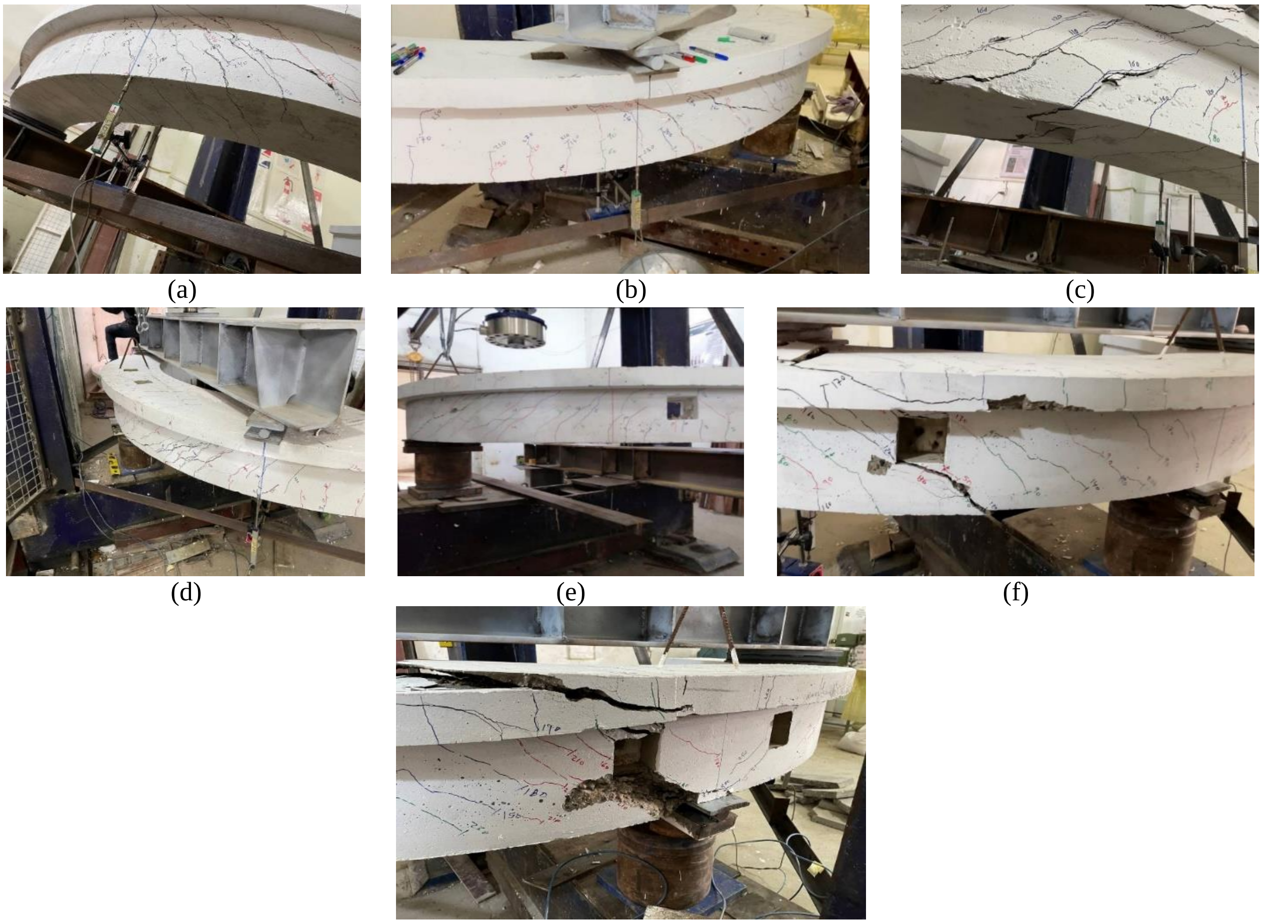

(a) (b) (c)
(d) (e) (f)
(g)

Figure 5. Specimens after failure: (a-g) specimens CB1- CB7.T82

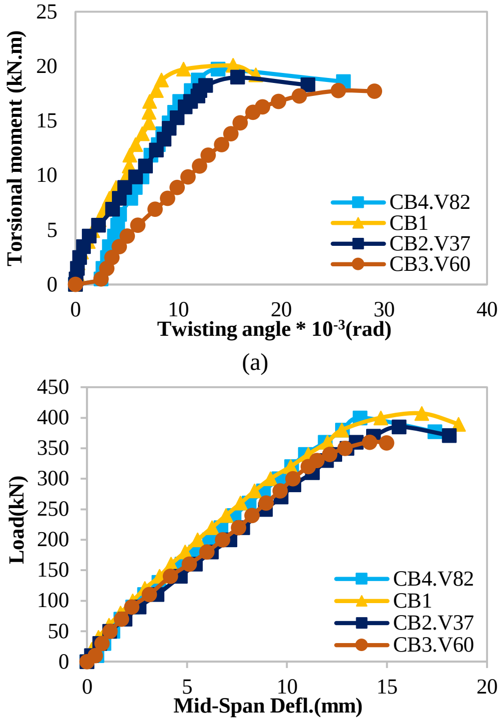
beam CB1 was measured 401 kN, which was less than that for CB1 by about 1.5%. The mode of failure and behavior (shape and widen) of flexural, torsional and shear cracks were similar to that of control beam CB1.

Figure 5(f) presents the photograph of specimen CB6.T60 after failure. Specimen CB6.T60 includes transverse opening positioned exactly at angle 60° measured from exterior support to the center of opening (in zone between the applied loads and internal support). Firstly, the specimen CB6.T60 was loaded until the first crack appears at a load of 50 kN at the skew corners (beam type) of the transverse opening, also flexural torsional and shear cracks were observed, versus the increase in applied load in a pattern hassling to control specimen CB1. As load increased further, rapid widening of diagonal cracks at the corners of transverse opening led to a frame type failure mode at opening zone which occurred at ultimate load of 218 kN, indicating a large reduction by about 46.4% when compared with a control CB1.

Figure 5(g) illustrates the photograph of specimen CB7.T82 after failure. Specimen CB7.T82 includes transverse opening spaced at distance d/2=125 mm from face of internal support (82° measured from exterior support to the center of opening). At load about 80 kN, cracks were noticed in the top and bottom skew corners of the transverse openings as a result of the concentration of stresses at these regions. In general, behavior of flexural, torsional and shear cracks were identical to that of control beam CB1. The ultimate load of beam CB7.T82 was about 331.48 kN by forming sudden shear cracks at top and bottom cords of the opening (frame type failure mode) near internal support. When compared to control CB1, the presence of a transverse opening at an angle (82°) resulted in an 18.66 % reduction in ultimate load capacity.

3. 2. Deformation Response

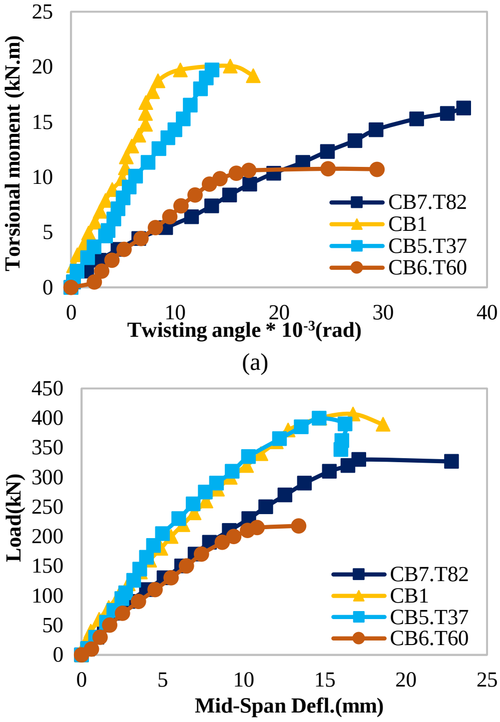
In this experimental work, deformations represent a deflection and twisting at midspan of the circular beams. Deformations response of circular beams could be described by the load-midspan deflection relationships as well as torsional moment-midspan twisting relationships at service loads (approximately 65% of maximum load) as proposed in [42]. Figures 6 and 7 represent the load-midspan deflection and torsional moment-midspan twisting response for specimens with vertical opening and transverse opening, respectively, compared to the control CB1. Furthermore, the service deflection, twisting and their contrast percentages compared with the control specimens were as shown in Table 3. The specimens (CB2.V37, CB3.V60 and CB4.V82) showed a clear increase in service midspan deflection and midspan twisting with a range (0-8.38%) and (21.6-103.3%), respectively, noticed that this increase corresponding to the reduction in ultimate load compared with the control



(a)

(b)

Figure 6. (a) Torsional moment-midspan twisting angle response for specimens with vertical opening (b) Load-midspan deflection response for specimens with vertical opening



(a)

(b)

Figure 7. (a) Torsional moment-midspan twisting angle response for specimens with transverse opening (b) Load-midspan deflection response for specimens with transverse opening

TABLE 3. Service deformations of tested specimens

Specimen designation	**Service deflection, Δs (mm)**[*]	$\frac{\Delta s_i - \Delta s_r}{\Delta s_r} \times 100\%^{(**)}$	**Service twisting, θs (Radian)$\times 10^{-3}$**	$\frac{\theta s_i - \theta s_r}{\theta s_r} \times 100\%^{(**)}$
CB1.L1	8	---	6.15	---
CB2.V37.L1	8.66	8.38	7.48	21.6
CB3.V60.L1	8	0	12.5	103.3
CB4.V82.L1	8.11	1.37	8.05	30.9
CB5.T37.L1	7.06	-11.75	8.8	43
CB6.T60.L1	6.43	19.6	10.53	71.2
CB7.T82.L1	9.45	18.1	20.55	234.1

[*] (Pser.=0.65 Pult.) [42]

[**] Δs_r= Service deflection of the reference CB; Δs_i=Service deflection of the considered CB

CB1. The specimens (CB6.T60 and CB7.T82) showed a large increase in service midspan deflection and midspan twisting with a range (18.1-19.6)% and (71.2-234.1)% respectively, noticed that this increase were with the reduction in ultimate load compared with the control CB1, while the specimen CB5.T37 did not show an increase in the service midspan deflection, while an increase in service midspan twisting was about 43%.

3. 3. Ductility

Ductility can be defined as the ability to sustain inelastic deformations without lacking of the load carrying capacity prior to failure. The vertical displacement at maximum load **Δu** divided by vertical displacement at service load **Δs** is used to estimate ductility factors in the ongoing investigation (approximately 65 percent of maximum load) as proposed in [42]. Ductility factor μ was defined as μ=($\frac{\Delta u}{\Delta s}$), which proposed in [42]. As shown in Table 4, the presence of vertical openings was led to a reduction in the ductility of specimens (CB2.V37, CB3.V60 and CB4.V82) by (13.88%, 15.3%, 19.62%), respectively, compared to the control CB1. Furthermore, the reduction in the ductility of specimens with transverse opening (CB5.T37, CB6.T60 and CB7.T82) was (0.5%, 0.5%, 13.88%), respectively, compared to the control CB1.

3. 4. Stiffness Criteria

Stiffness $\boldsymbol{\kappa}$ is defined as the amount of force necessary to cause unit deformation in a member. The slope of the secant drawn to each cycle in the hysterical curve at loading 0.75 times the maximum load of that cycle was measured as stiffness criteria as proposed in literature [43]. In this work Stiffness $\boldsymbol{\kappa}$ was defined as the ratio between the (0.75 of max applied load (P_{max})) and corresponding displacement, considering that each specimen subjecting to only one cycle of loading, Table 5 listed the variation in Stiffness $\boldsymbol{\kappa}$ compared to the control specimen CB1, where $\boldsymbol{\kappa}_i$ is stiffness of the considered beam and $\boldsymbol{\kappa}_r$ stiffness of the control beam. As a comparison with a control CB1, the stiffness of specimens with vertical opening showed stiffness degradation by about (14.11%, 10.2% and 3.98%) for (CB2.V37, CB3.V60 and CB4.V82), respectively. As specimens with transverse opening, a degradation was about (31.78% and 33%) for (CB6.T60 and CB7.T82), respectively, while the presence of opening at an angle (37°) for specimen CB5.T37 had no effect on its stiffness compared to the control CB1.

TABLE 4. Ductility factor of tested specimens

Specimen Designation	**Service Deflection, Δs (mm)**[*]	**Ultimate Deflection, Δu (mm)**	**Ductility Factor, μ ($\frac{\Delta u}{\Delta s}$)**	$\frac{\mu_i - \mu_r}{\mu_r} \times 100\%^{(**)}$
CB1.L1	8	16.75	2.09	---
CB2.V37.L1	8.66	15.6	1.8	-13.88
CB3.V60.L1	8	14.14	1.77	-15.3
CB4.V82.L1	8.11	13.65	1.68	-19.62
CB5.T37.L1	7.06	14.66	2.08	-0.5
CB6.T60.L1	6.43	13.4	2.08	-0.5
CB7.T82.L1	9.45	17.1	1.8	-13.88

[*] (Pser=0.65 Pult.) [42]

[**] μ_r= Ductility of the control CB; μ_i= Ductility of the considered CB

TABLE 5. Stiffness criteria of tested specimens

Specimen Designation	**0.75 P_{max}^{*} (kN)**	**Deflection at 0.75 P_{max} (mm)**	**Stiffness, κ (kN/mm)**	$\frac{\kappa_i-\kappa_r}{\kappa_r}\times100\%^{(**)}$
CB1	305.44	9.37	32.6	----
CB2.V37	289.3	10.35	28	-14.11
CB3.V60	270.22	9.23	29.27	-10.2
CB4.V82	300.4	9.6	31.3	-3.98
CB5.T37	300.75	9.03	33.3	2.14
CB6.T60	163.5	7.35	22.24	-31.78
CB7.T82	248.61	11.38	21.84	-33

* max applied load

** κ_i =Stiffness of the considered CB; κ_r = Stiffness of the control CB

4. CONCLUSIONS

The current researchers focused into how the inclusion of an opening affects the structural behavior of horizontally curved box beams. The following conclusions may be drawn from the experimental findings of this study.

1. The ultimate load capacity was decreased for specimens with vertical opening (CB2.V37, CB3.V60and CB4.V82) by about (5%, 11.5% and 1.5%) respectively, while for specimens with transverse opening (CB5.T37, CB6.T60 and CB7.T82) were about (1.5%, 46.4% and 18.66%) respectively, as compared to the control CB1. It can be concluded that the presence of opening at an angle 60° where maximum shear and torsion in both directions, caused a largest lack in ultimate load capacity of the beam.
2. As mode of failure, no alteration was observed in specimens CB2.V37, CB4.V82 and CB5.T37, while for specimens CB3.V60, CB6.T60 and CB7.T82 was conversion from torsional-shear failure mode of control specimen CB1 to frame- type failure at opening zone.
3. Service response for all specimens with opening in terms of deflection and twisting angle at midspan of the circular beams were adversely affected (increased) when compared with the control specimen CB1.
4. The ductility was decreased for all specimens with opening (CB2.V37, CB3.V60, CB4.V82, CB5.T37, CB6.T60 and CB7.T82), as a percent was about (13.88%, 15.3%, 19.62%, 0.5%, 0.5% and 13.88%), respectively, compared with that of control specimen CB1.
5. The specimens containing opening were shown a clear degradation in its stiffness, except the stiffness of specimen CB5.T37 was not affected as a comparison with stiffness of control specimen CB1.

5. REFERENCES

1. Gupta, P. K., Singh, K. K., and Mishra, A. "parametric study on behaviour of box-girder bridges using finite element method." ***Asian Journal of Civil Engineering (Building and Housing)***, Vol. 11, No. 1, (2010), 135–148.
2. Wasti, S. T., and Scordelis, A. C. "Comparative Structural Behavior of Straight, Curved and Skew Reinforced Concrete Box Girder Bridge Models." In Analysis and Design of Bridges (pp. 191–211). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-009-6122-7_7
3. Kurian, B., and Menon, D. "Estimation of Collapse Load of Single-Cell Concrete Box-Girder Bridges." ***Journal of Bridge Engineering***, Vol. 12, No. 4, (2007), 518–526. https://doi.org/10.1061/(ASCE)1084-0702(2007)12:4(518)
4. Arendts, J. G. Load distribution in simply supported concrete box girder highway bridges. Iowa State University, 1969.
5. Razaqpur, A. G., Nofal, M., and Mirza, M. S. "Nonlinear analysis of prestressed concrete box girder bridges under flexure." ***Canadian Journal of Civil Engineering***, Vol. 16, No. 6, (1989), 845–853. https://doi.org/10.1139/l89-127
6. Luo, Q. Z., Tang, J., and Li, Q. S. "Calculation of Moments on Top Slab in Single-Cell Box Girders." ***Journal of Structural Engineering***, Vol. 129, No. 1, (2003), 130–134. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:1(130)
7. Subramani, T., Subramani, M., and Prasath, K. "Analysis of Three Dimensional Horizontal Reinforced Concrete Curved Beam Using Ansys." ***International Journal of Engineering Research and Applications***, Vol. 4, No. 6, (2014), 156–161. Retrieved from www.ijera.com
8. Al-Tameemi, H. A., Ali, A., and Attiyah, A. N. "Three-dimensional nonlinear finite element analysis of reinforced concrete horizontally curved deep beams." ***Journal of Babylon University/Engineering Sciences***, Vol. 18, No. 1, (2010), 1–18. Retrieved from https://www.researchgate.net/profile/Haider-Al-Tameemi/publication/332565074_Three-Dimensional_Nonlinear_Finite_Element_Analysis_of_Reinforced_Concrete_Horizontally_Curved_Deep_Beams/data/5cbde2e4a6fdcc1d49a85baf/3DNFEAHCDB-H-A-J.pdf
9. Al-Mutairee, H. M. K. "Effect of Non-Uniform Distribution of Longitudinal Reinforcement on the Behavior of Reinforced Concrete Horizontally Curved Beams with Fixed-Ends." ***Journal of University of Babylon***, Vol. 21, No. 3, (2013), 826–838. Retrieved from https://www.iasj.net/iasj/article/78025
10. Badawy, H. E. I., McMullen, A. E., and Jordaan, I. J. "Effect of Shear on Collapse of Curved Beams." ***Journal of the Structural Division***, Vol. 103, No. 9, (1977), 1849–1866. https://doi.org/10.1061/JSDEAG.0004725
11. Chu, K.-H., and Thelen, A. "Plastic Analysis of Circular Balcony Girders." ***Journal of the Structural Division***, Vol. 89, No. 6, (1963), 159–186. https://doi.org/10.1061/JSDEAG.0000999
12. Hsu, T. T. C., Inan, M., and Fonticiella, L. "Behavior of reinforced concrete horizontally curved beams." ***Journal Proceedings,*** Vol. 75, (1978), 112–123. Retrieved from

https://www.concrete.org/restrictedcountry.aspx

13. Jordaan, I. J., Khalifa, M. M. A., and McMullen, A. E. "Collapse of Curved Reinforced Concrete Beams." ***Journal of the Structural Division***, Vol. 100, No. 11, (1974), 2255–2269. https://doi.org/10.1061/JSDEAG.0003931

14. Khalifa, M. M. A. "Collapse of reinforced concrete beams curved in plan." In Thesis presented to the University of Calgary,at Calgary, Alberta, Canada, in partial fulfillment of requirements for the degree of Master of Science, (1972).

15. Mansur, M. A., and Rangan, B. V. "Study of design methods for reinforced concrete curved beams." ***Journal Proceedings***, Vol. 78, (1981), 226–254. Retrieved from https://www.concrete.org/restrictedcountry.aspx

16. Burton, K. T. "Influence of Embedded Service Ducts on the Strength of Continuous Reinforced Concrete T-Beams." ***Journal Proceedings***, Vol. 62, (1965), 1327–1344. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&i=7748&m=details&i=7748

17. Dallal, M. S. "Behavior and design of reinforced concrete T-beams with large openings in the webs /," (1968). Retrieved from https://hdl.handle.net/11244/2426

18. Mansur, M. A. "Deflections of reinforced concrete beams with web openings." ***ACI Structural Journal***, (1992), 389. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.573.8180

19. Mansur, M. A. "Effect of openings on the behaviour and strength of R/C beams in shear." ***Cement and Concrete Composites***, Vol. 20, No. 6, (1998), 477–486. https://doi.org/10.1016/S0958-9465(98)00030-4

20. Mansur, M. A., and Tan, K.-H. Concrete beams with openings: analysis and design (Vol. 20). CRC Press, 1979.

21. Mansur, M. A. "Design of reinforced concrete beams with web openings." In Proceedings of the 6th Asia-Pacific structural engineering and construction conference (ASPEC 2006) (pp. 5–6). Kuala Lumpur Malaysia, 2006. Retrieved from https://www.sefindia.org/forum/files/mamansur2006_designofreinforcedconcretebeams_with_openings_413.pdf

22. Nasser, K. W., Acavalos, A., and Daniel, H. R. "Behavior and design of large openings in reinforced concrete beams." ***Journal Proceedings,*** Vol. 64, (1967), 25–33. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=7540

23. Saksena, N. H., and Patel, P. "Experimental study of reinforced concrete beam with web openings." ***International Journal of Advanced Engineering Research and Studies-India***, Vol. 2, No. 3, (2013), 66–68.

24. Salam, S. A. "Beams with openings under different stress conditions." In Conference on Our World in Concrete and Structures, Singapore (pp. 25–26), 1985.

25. Somes, N. F., and Corley, W. G. "Circular openings in webs of continuous beams." ***Special Publication***, Vol. 42, (1974), 359–398. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/17293

26. Tan, K.-H., Mansur, M. A., and Huang, L.-M. "Reinforced concrete T-beams with large web openings in positive and negative moment regions." ***Structural Journal***, Vol. 93, No. 3, (1996), 277–289. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/9687

27. Mansur, M. A., Tan, K.-H., and Wei, W. "Effects of creating an opening in existing beams." ***Structural Journal***, Vol. 96, No. 6, (1999), 899–905. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/785

28. Hanson, J. M. "Square openings in webs of continuous joists." Portland Cement Assoc R & D Lab Bull, (1969).

29. Chin, S. C., Shafiq, N., and Nuruddin, M. F. "FRP as strengthening material for Reinforced Concrete beams with openings — A review." ***KSCE Journal of Civil Engineering***, Vol. 19, No. 1, (2015), 213–219. https://doi.org/10.1007/s12205-011-0162-8

30. Ahmed, A., Fayyadh, M. M., Naganathan, S., and Nasharuddin, K. "Reinforced concrete beams with web openings: A state of the art review." ***Materials & Design***, Vol. 40, (2012), 90–102. https://doi.org/10.1016/j.matdes.2012.03.001

31. Mansur, M. A., and Hasnat, A. "Concrete Beams with Small Opening under Torsion." ***Journal of the Structural Division***, Vol. 105, No. 11, (1979), 2433–2447. https://doi.org/10.1061/JSDEAG.0005286

32. Mansur, M. A., and Alwis, W. A. M. "Reinforced fibre concrete deep beams with web openings." ***International Journal of Cement Composites and Lightweight Concrete***, Vol. 6, No. 4, (1984), 263–271. https://doi.org/10.1016/0262-5075(84)90021-6

33. Mansur, M. A., Tan, K. H., and Lee, S. "Collapse Loads of R/C Beams with Large Openings." ***Journal of Structural Engineering***, Vol. 110, No. 11, (1984), 2602–2618. https://doi.org/10.1061/(ASCE)0733-9445(1984)110:11(2602)

34. Mansur, M. A., and Paramasivam, P. "Reinforced concrete beams with small opening in bending and torsion." ***Journal Proceedings,*** Vol. 81, (1984), 180–185. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/10677

35. Mansur, M. A., Tan, K. H., and Lee, S. L. "Design method for reinforced concrete beams with large openings." ***Journal Proceedings,*** Vol. 82, (1985), 517–524. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/10364

36. Mansur, M. A., Lee, Y. F., Tan, K. H., and Lee, S. L. "Tests on RC Continuous Beams with Openings." ***Journal of Structural Engineering***, Vol. 117, No. 6, (1991), 1593–1606. https://doi.org/10.1061/(ASCE)0733-9445(1991)117:6(1593)

37. Ali, A., and Hemzah, S. A. "Nonlinear analysis for behavior of RC horizontally semicircular curved beams with openings and strengthened by CFRP laminates." ***International Journal of Scientific & Technology Research***, Vol. 3, No. 8, (2014), 136–145. Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.644.1460&rep=rep1&type=pdf

38. "The European Guidelines for Self- Compacting Concrete; Specification, Production and Use," (2005). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.121.6496&rep=rep1&type=pdf

39. "ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19), Farmington Hills, Michigan," (2019).

40. "ACI Committee 314 'Guide to Simplified Design for Reinforced Concrete Buildings' (ACI 314R-16), Farmington Hills, Michigan," (2016).

41. "AASHTO LRFD Bridge Design Specifications 'American Association of State Highway and Transportation Officials' USA, Fifth Edition," (2010).

42. Russell, J. S. "Prestrectives in Civil Engineering." Commemorating the 150th Anniversary of the American Society of Civil Engineering, ASCE Publications, (2003), 375.

43. Ghobarah, A., and Said, A. "Seismic rehabilitation of beam-column joints using FRP laminates." ***Journal of Earthquake Engineering***, Vol. 5, No. 1, (2001), 113–129. https://doi.org/10.1142/S1363246901000297

Persian Abstract

چکیده

این کار به بررسی رفتار بتن آرمه سازه‌ای تیرهای جعبه منحنی افقی با و بدون باز شده اختصاص دارد. هفت تیر جعبه‌ای دایره‌ای افقی در کار آزمایشی مورد بررسی قرار گرفت، یکی بدون بازشو، سه تیر با بازشو عمودی و سه تیر با بازشو عرضی. برنامه آزمون شامل متغیرهای اصلی است. جهت بازشو، محل بازشو از طریق پروفیل تیرهای منحنی (اثر ترکیب نیروهای داخلی). تیرها به صورت یک تیر پیوسته با دو دهانه آزمایش شدند که هر دهانه یک چهارم دایره را نشان می‌دهد و تحت تأثیر دو بار نقطه‌ای هر بار در بالای وسط دهانه تیر قرار دارد. یافته‌ها نشان می‌دهد که ظرفیت بار نهایی برای همه نمونه‌ها (CB2.V37، CB3.V60، CB4.V82، CB5.T37، CB6.T60 و CB7.T82) حدود (۵، ۱۱/۵، ۱/۵، ۱/۵، ٤٦/٤ و ۱۸/٦٦ درصد) به ترتیب در مقایسه با کنترل CB1 کاهش یافته است. و در مقایسه با نمونه کنترل CB1، همه نمونه‌ها نشان‌دهنده افزایش در تغییر شکل‌های سرویس از نظر انحراف و زاویه پیچش در وسط پرتوهای دایره‌ای بودند. شکل‌پذیری برای همه نمونه‌های دارای بازشدگی (CB2.V37، CB3.V60، CB4.V82، CB5.T37، CB6.T60 و CB7.T82)، به عنوان درصدی در حدود (۱۳/۸۸، ۱۵/۳، ۱۹/٦۲، ۰/۵، ۰/۵، و ۱۳/۸۸) به ترتیب، در مقایسه با نمونه CB1 شاهد کاهش یافت. در نتیجه، به طور کلی، یک تخریب واضح با درصدهای مختلف در رفتار کلی سازه تیرهای جعبه‌ای منحنی افقی حاوی دهانه با توجه به موقعیت و جهت بازشوها، در این مطالعه بازشوهای عرضی در ٦۰ درجه، که در آن بازشو تحت حداکثر ترکیبی (برش و پیچش) منجر به کاهش فاجعه بار در عملکرد ساختاری تیر جعبه منحنی افقی شد.