The 2015 World Congress on
Advances in Structural Engineering and Mechanics (ASEM15)
Incheon, Korea, August 25-29, 2015

Proposed recommendations for the design of reinforced concrete beams with openings

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ABSTRACT

This study investigates the behaviour of simply supported and continuous RC beams with openings loaded by either a uniformly-distributed load, or a single, central concentrated load. The focus is on developing simplified recommendations for the design of RC beams with openings. For this purpose, relevant published research is compiled and critically reviewed including both experimental and theoretical works. Then, numerous RC beams with openings are analyzed using the finite element package ansys to complement the already published research. The beams analyzed in this study are selected to investigate the effects of the following: (1) opening location; (2) boundary conditions: results of beams with two hinged supports are compared to those of hinged-roller and fixed-fixed beams; (3) span-to-depth ratio: the performance of beams with span-to-depth ratios of 5.8 and 11.8 is compared for both cases of hinged-hinged and hinged-roller support conditions; (4) tension reinforcement ratio: reinforcement ratios ranging from the minimum to the maximum code limits are considered; and (5) tension reinforcement development detail at hinged supports. Generally, it is noticed that in beams with opening located near supports fail in shear mode, while beams with opening located at midspan fail in flexure or shear-flexure modes depending on type of load (uniform or concentrated). Nevertheless, openings at span quarter points are more critical to beam strength than central openings.

1. INTRODUCTION

Transverse openings in reinforced concrete beams are often needed to provide passage for utility ducts that accommodate essential services such as water supply, electricity, telephone, and computer network. Passing these ducts through transverse openings, rather than below beam soffits, reduces the height of the structure and leads

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to a better, more economical design. However, presence of openings in beams produces discontinuities in the normal flow of stresses and causes stress concentration and early cracking in the opening region. Special reinforcement should therefore be provided to control crack widths and prevent possible premature failure (e.g. Mansur et al. (1984) and Ramadan et al. (2009b&c)). The studies in the literature mostly focus on developing design guidelines for RC beams with single opening, but research on beams with multiple openings was also reported, e.g. Aykac et al. (2013). Besides, behavior of high-strength concrete beams with openings was investigated by Abd El-Shafy et al. (2005) and by Ramadan and Kansouh (2006). Furthermore, while a large portion of published work addresses beams with rectangular sections, Abd El-Shafy et al. (2005) and Alazhary (2011) considered beams with T-shaped sections. Comprehensive reviews on the subject have been recently reported (Ahmed et al. (2012) and Aykac et al. (2013)) and shall not be repeated here for brevity. Nevertheless, the following discussion summarizes the significant findings of previous studies related to the behavior of shallow beams with openings.

Mansur et al. (1985) proposed a design method for RC beams with large rectangular opening subjected to point load. Later, Mansur et al. (1992) developed a method for calculating the deflections of RC beams with a large rectangular opening by assuming that a contraflexure point forms at mid-length of each chord in Vierendeel mechanism. Al-shaarbaf et al. (2007) compared the experimental results obtained by Mansur et al. (1985) with those of the finite element method where good agreement was shown. Their results showed that the concrete compressive strength has significant effect in the post cracking stiffness and the ultimate load of beams with opening.

Ramadan et al. (2009a&c) examined the behavior of simply supported reinforced concrete beams having a single rectangular opening subjected to a single central concentrated load. In this study, the opening with depth ratio (h0/D= 0.5), caused up to 40% reduction in beam strength. The effect of opening presence decreased when it was shifted towards tensioned side but increased when it was shifted towards the compressed side. Ramadan et al. (2009b) investigated the behavior of simply supported and continuous reinforced concrete beams having a single rectangular opening subjected to uniform distributed load. In this study, the amount of reduction in both the ultimate load and the stiffness of RC beams was found to be significantly affected by the opening proximity to support, the opening height, and the opening length, but slightly affected by tension and compression reinforcement ratios. Alazhary (2011) studied the effect of openings on RC beams with R- and T- sections under uniform load and point load. In this study, the effect of opening height, length, and location was similar for both R- and T-section beams subjected to point load. The effect of opening presence in RC beams has more effect on R-section beams than in T-section ones under uniform load. Ahmed et al. (2012) reviewed the existing work related to RC beams with openings. Aykac et al. (2013) investigated the influence of multiple web openings along the length of an RC beam on its flexural behavior. The study revealed that the length of the plastic failure mechanism increased in the presence of multiple openings compared to beams with a single opening.

From the previous reviews of literature it is clear that the presence of one large opening in a reinforced concrete beam could have significant effects on the beam structural performance in terms of cracking load, failure load, crack pattern, and stress distribution. The severity of these effects, however, depends on many factors including type of loading, opening size, and opening location. Despite the numerous published research works, it is obvious that there are gaps that need to be filled to develop adequate, yet simplified guidelines appropriate for inclusion in design codes. The need for such guidelines is evident from the scarce references to beams with openings in design codes and specifications. Currently, reference to beams with openings is limited to consideration of effective area in shear design in some codes (ACI-318 (2008) and (CSA-A23.3 (2004)); accounts for very small openings only in few other codes (AIJ (1994) and NZS-3101 (2006)); and is absent for the rest. This paper attempts to complement the published data and to provide a further step towards the development of a complete set of simplified design guidelines. To this end, numerous simply supported and continuous RC beams with openings are analyzed under the effect of two load configurations: uniformly-distributed; and concentrated loads.

2. OBJECTIVES AND SCOPE OF STUDY

The purpose of this study is to investigate the effect of opening presence on the behavior of reinforced concrete beams. It addresses the effects of the following aspects:

(1) Boundary conditions: results of hinged- hinged, hinged-roller as well as continuous beams are presented and compared;
(2) Span-to-depth ratio: beams with span-to-depth ratios of 5.8 and 11.8 are investigated;
(3) Tension reinforcement: beams with openings having tension reinforcement ratios ranging from the minimum to the maximum code limitsare analyzed;
(4) Opening location: beams with openings at quarter-span andat mid-span points are analyzed;
(5) Tension reinforcement development at hinged supports;
(6) Load type: two load configurations are considered: uniform load and central concentrated load.

These objectives are fulfilled by analyzing nine series of beams, as detailed in Table 1 and Fig. 1, using the ANSYS software package. The results discussed include the reduction in both cracking and failure loads due to presence of openings. All beams have rectangular cross section (200mm wide and 500mm deep) and a compression-to-tension reinforcement ratio of α=As'/AS=0.2. These openings are located at mid height of the beam. Series B is the same as Series A, but have two-hinged ends instead of hinged-roller ends. Besides, Series C and D are similar to Series A and B, except that they have a span-to-depth ratio of about double that of Series A and B. Series E has fixed-fixed ends. Finally, Series F to I are analyzed to investigate the effect of the amount of tension reinforcement. A number of beams without openings (i.e. solid) are also analyzed and their results are used as the reference. Figure 1 also defines the problem variables.

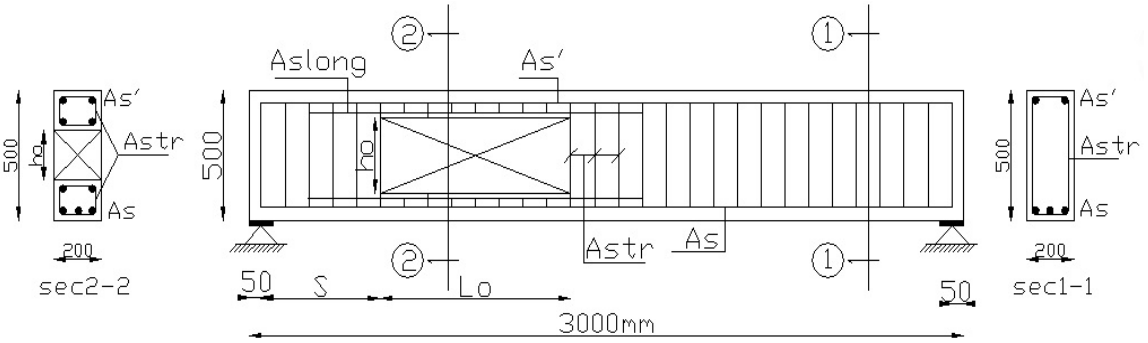


Fig. 1 Dimension and reinforcement details of simply supported beams with opening

The beams in Table 1 were provided with special reinforcement details around the opening following Art. 9.3.11 of NZS 3101(2006) and then re-analyzed. The special details included additional stirrups above and below the opening to resist one and half the shear force across the opening, and additional stirrups on both sides of the opening to resist double this shear force.

Table 1 Summary of analyzed beams' features and variables (see Fig. 1 for geometric configuration)

Seri-es	Constant/Variable Controlling Data and Their Ranges				Load type	Boundary Conditions	No of beams*
	Opening Size	Opening Location, (S/L)	Span-to-depth ratio	Tension Reinforcement ratio, (μ/μ_{max})			
A	h_0/D=0.58 L_0/L=0.27	0.0, 0.167 &0.35	5.8	0.5	C	H-R	4
B		0.0, 0.167 &0.35	5.8			H-H	4
C		0.0, 0.167 &0.35	11.8			H-R	4
D		0.0, 0.167 &0.35	11.8			H-H	4
E		0.167, 0.333 &0.367	5.8			F-F	4
F	h_0/D=0.58 L_0/L=0.20	quarter span and midspan	5.8	0.25, 0.4, 0.5& 1.0	U	H-R	12
G					C	H-R	11
H					U	F-F	12
I					C	F-F	11

Notes:
* These numbers include reference beam(s) without openings.
U= uniform distributed load on beam full length; C= single concentrated load at beam midspan. H= hinged; R=roller; F= fixed. μ= tension reinforcement ratio; μ_{max}= 0.0125 is maximum tension reinforcement ratio according to ECP-203 for f_{cu}= 25MPa which equals 8⁄9 of ACI-318's ρ_{max}.

3. DEVELOPMENT OF STRUCTURAL MODELS USING ANSYS

3.1 Material Properties

Concrete is modeled as a multi-linear isotropic material with characteristic cubic compressive strength of fcu= 25MPa (fc'=20MPa), an initial modulus of elasticity of Ec= 22,000MPa, a flexure tensile strength of fctr= 3MPa, and a Poisson's ratio of v= 0.2 using the eight-node solid element SOLID65. Further, the steel reinforcement is assumed to be an elastic-perfectly plastic material with identical behaviors in tension and compression. The elastic modulus and Poisson's ratio for steel are taken 210,000 MPa and 0.3, respectively. LINK180, a three-dimensional spar element with plasticity is employed to model the beam reinforcement. The yield strength of steel used for stirrups and longitudinal reinforcement is equal to 240 MPa and 360 MPa, respectively. Finally, the thick steel plates simulating the relatively rigid load/support zones are assumed to be isotropic and linearly elastic for which the SOLIED45 element is adopted following Tian et al. (1995).

3.2 Loading and Boundary Conditions

The single concentrated load is simulated by a series of point loads on all nodes across the steel plate located at the top of the beam midspan. Nevertheless, the uniformly distributed load is divided into a series of concentrated loads on all nodes across the beam top "loaded" surface.

3.3 Meshing

A convergence study was carried out to determine an appropriate mesh density. Various mesh sizes were examined in ANSYS. The beam mesh was selected in a way that the nodes of solid elements representing concrete match with those of bar elements simulating the reinforcement. Full bond is assumed between concrete and reinforcement Fig. 2 shows the mesh of a typical beam with opening.

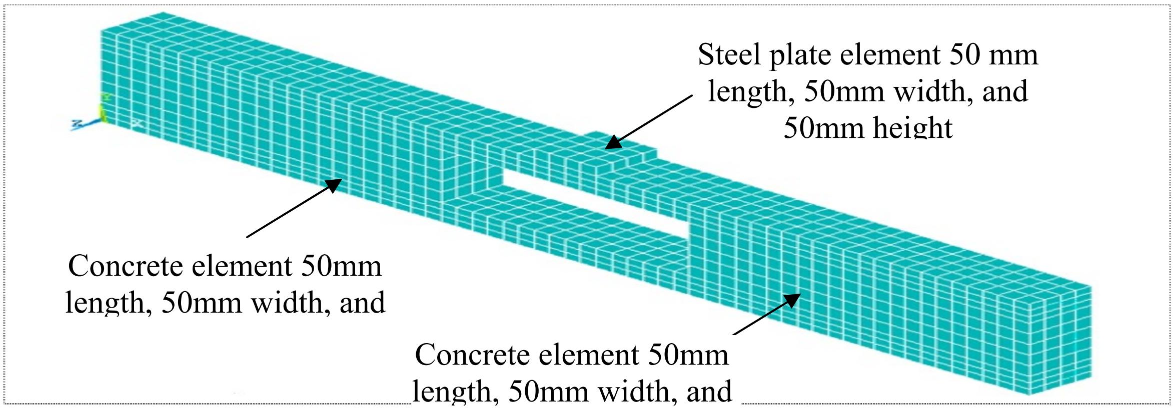


Fig. 2 Meshing of a typical beam with opening

4. RESULTS AND DISCUSSIONS

4.1 Cracking and failure loads for simply supported beams

The values of cracking and failure loads from finite element analysis of RC analyzed beams in series (A and B) are presented in Table 2 and Figs. 3 and 4. Note that the ANSYS result for the solid beam in series A (Pcr = 54kN) compares with that of (ECP-203) (Pcr = 50.34kN). Also, the failure load of solid beam in series A from ANSYS result (Pf = 120kN) compress with that of (ECP-203) (Pf = 115kN). This remark proved to be valid for all solid beams as shown below.

4.1.1 Effect of opening location

The first crack appeared in all cases of beams with opening at the external lowest corner (nearer to the support) of the opening. As the relative influence of bending moment compared to that of shearing force increases as the opening is shifted away of the nearest support, the first crack appeared in beams with opening located at/near the support faster (i.e. at smaller loads) than that in beams with opening located away from the support. End openings resulted in an average reduction of 80% and 82% in the beams' cracking and failure loads, respectively, relative to the corresponding beams without opening. This reduction slightly decreased opening shift away of the support and became about 70% and 65%, respectively, at S=D. After that, the reduction continued to decrease and reached about 40% and 50%, respectively, for beams with central opening. For beams with special details satisfying NZS 3101(2006), the reduction in cracking and failure loads was 63% and 50%, respectively, for end openings; and 20% and 16%, respectively, for central openings. Note, however, that the opening h0=0.58D is larger than the maximum allowed by NZS (h0=0.4D).

Table 2 Cracking and failure loads of the analyzed simply supported beams in series (A and B)

Series	Analyzed beams	Cracking load (kN)	Failure load (kN)	Cracking load (kN) with Special Details	Failure load (kN) with Special Details
A (Hinged-roller ends)	Solid beam (A)	54.0 (50.34)*	120.0 (115.0)*	N/A	N/A
	End opening (A1)	9.0	22.5	19.2	58.5
	Opening at S=D (A2)	12.6	42.0	26.6	72.0
	Central opening (A3)	25.2	63.0	43.2	100.8
B (Two hinged ends)	Solid beam (B)	76.5	170.0	N/A	N/A
	End opening (B1)	10.8	27.0	32.9	98.6
	At S=D (B2)	15.3	51.0	41.3	120.7
	Central opening (B3)	30	75.0	64.3	151.3

* Values calculated using (ECP-203)

4.1.2 Effect of boundary condition

Comparing the results of hinged-hinged beams (series B) to that of the corresponding hinged- roller beams (series A) in Figs. 3 and 4 indicates the benefits of the arch action developed in series B due to restraining the x-translation at both supports. The arch action increased the crack and failure loads by an average value of 80% and 40%, respectively, for solid beams, and by 25% and 20%, respectively, for beams with openings.

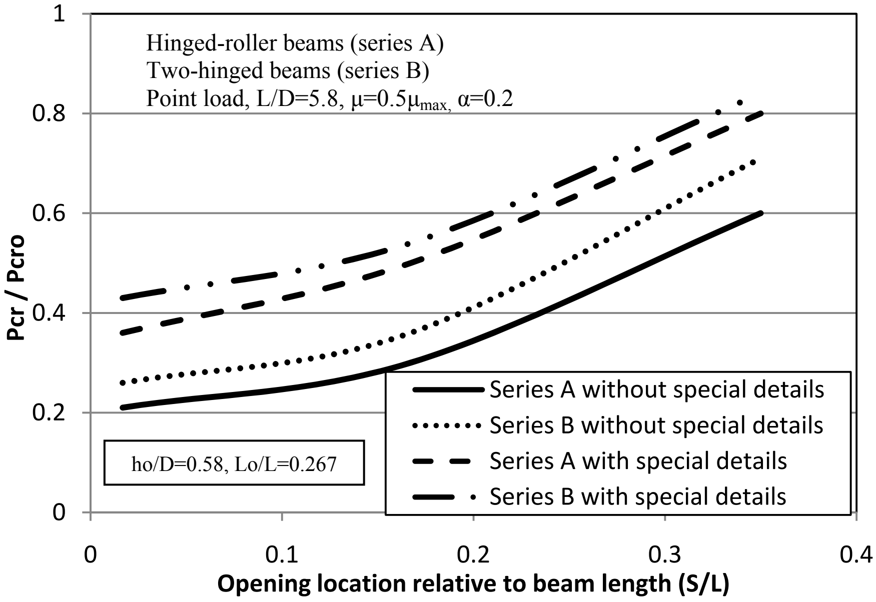


Fig. 3 Effect of opening location on the cracking load of the analyzed beams in series A and B

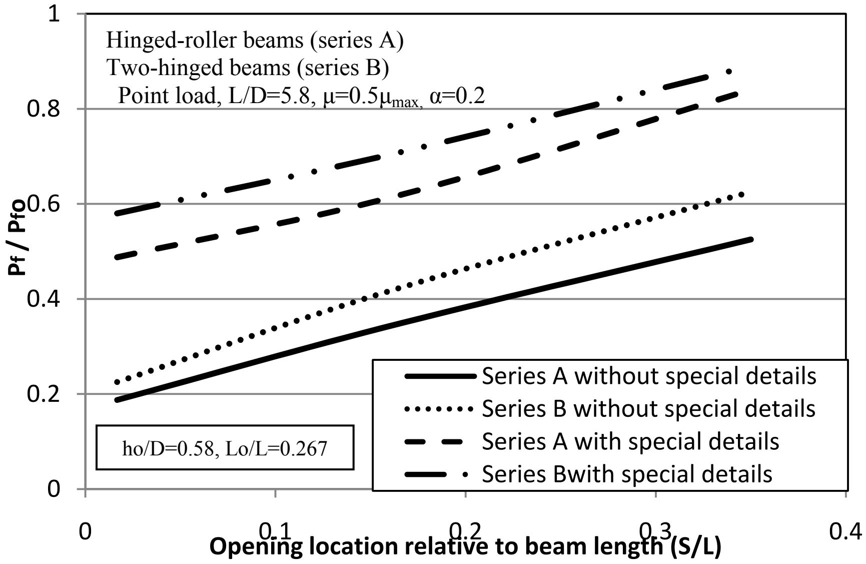


Fig. 4 Effect of opening location on the failure load of the analyzed beams in series A and B

4.1.3 Effect of span-to-depth ratio

Table 3 and Figs. 5 and 6 present values of cracking and failure loads obtained for beams with span-to-depth ratio of L/D=11.8 (series C and D) without and with special details. These figures show that the reduction in cracking and failure loads due to opening presence for shallower beams (series C and D with L/D=11.8) is generally less than that for deeper beams (series A and B with L/D=5.8). Nevertheless, the benefit of hinged-hinged boundary condition in reducing the detrimental effects of opening presence becomes more pronounced in deeper beams particularly for openings near the supports.

Table 3 Cracking and failure loads of the analyzed simply supported beams in series (C and D)

Series	Analyzed beams	Cracking load (kN)	Failure load (kN)	Cracking load (kN) with Special Details	Failure load (kN) with Special Details
C (Hinged-roller ends)	Solid beam (C)	34.0 (29.54)*	65.4 (57.5)*	N/A	N/A
	End opening (C1)	11.22	25.11	14.0	38.0
	Opening at S=D (C2)	13.6	35.19	18.0	45.8
	Central opening (C3)	22.78	62.13	27.9	65.4
D (Two hinged ends)	Solid beam (D)	43.88	87.75	N/A	N/A
	End opening (D1)	16.24	48.26	21.1	55.7
	At S=D (D2)	21.06	57.26	26.3	65.8
	Central opening (D3)	34.23	87.75	37.7	87.75

* Values calculated using (ECP-203)

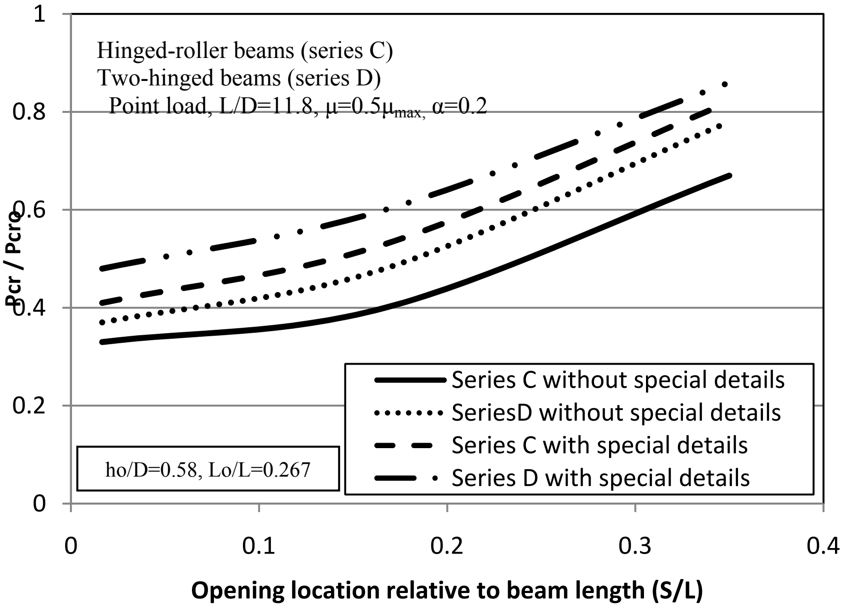


Fig. 5 Effect of opening location on the cracking load of the analyzed beams in series C and D

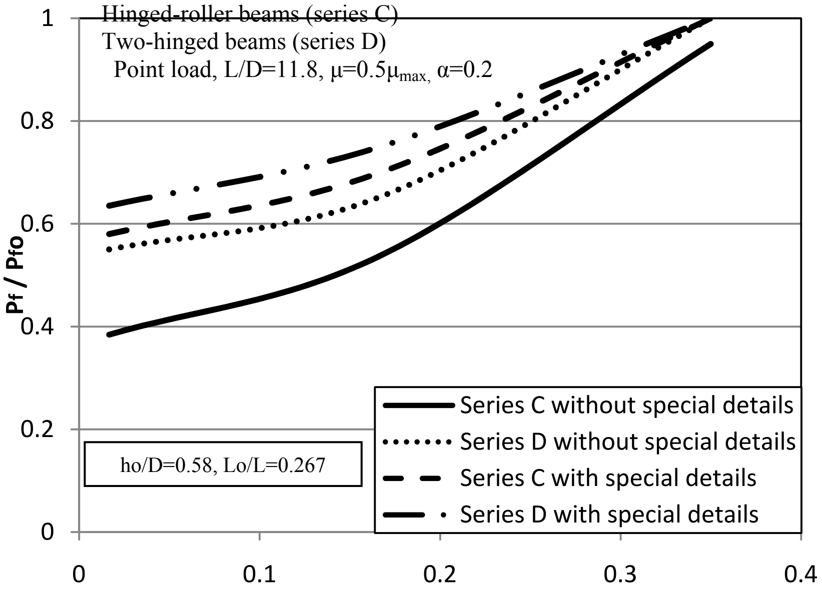


Fig. 6 Effect of opening location on the failure load of the analyzed beams in series C and D

4.2 Cracking and failure loads for continuous beams

Cracking and failure loads for continuous beams subjected to a concentrated load at midpoint are presented in Table 4 and Fig. 7. Fig. 7 indicates that the reduction in cracking and failure loads relative to those of beam without opening is highest (81% and 70%, respectively) for openings located close to the supports due to significant bending moment and shearing force. This reduction slightly decreases as the opening moves away of the support and becomes (63% and 58%, respectively) for central openings. Further, for beams provided with special reinforcement around the opening, the reduction in cracking and failure loads was (67% and 60%, respectively) for openings located close to the supports and (50% and 32%, respectively) for central openings. Thus, the use of special reinforcement around the opening in this case reduced, but could not eliminate the drawback of opening presence.

Table 4 Cracking and failure loads for continuous beams (series E)

Analyzed beams	Cracking load (kN)	Failure load (kN)	Cracking load (kN) with Special Details	Failure load (kN) with Special Details
Solid beam	96.0 (91.5)*	240 (233.5)*	96.0 (91.5)*	240 (233.5)*
Opening at S=D	18.0	72.0	31.7	96.0
Opening at S=2D	33.6	96.0	44.2	148.8
Central opening	35.7	102.0	48.0	163.2

* Values calculated using (ECP-203)

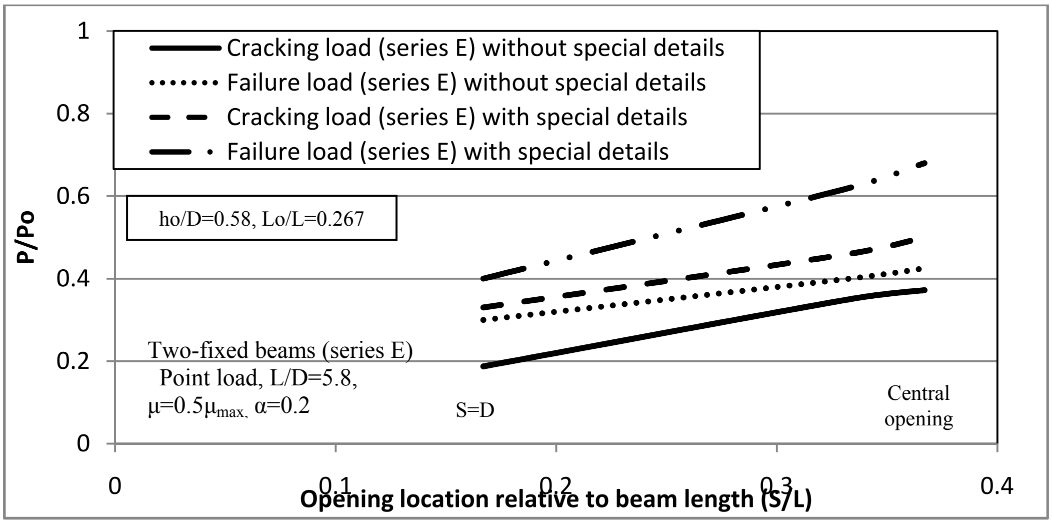


Fig. 7 Effect of opening location on the cracking and failure loads of continuous beams

4.3 Effect of tension reinforcement ratios on cracking and failure loads

This section investigates the effect of beam's tension reinforcement ratio on its performance in presence of opening. Simply supported beams are treated followed by continuous beams.

4.3.1 Simply supported beams

Tables 5 & 6 and Figs. 8 & 9 present values of cracking and failure loads obtained using ANSYS for beams with openings subject to uniform load. They show that the reduction in the cracking and failure loads for beams with central opening relative to that of corresponding beams without opening is negligible for small to moderate tension reinforcement ratios (up to μ=0.5μmax), but become significant for beams with (μ=μmax) under both types of loading. However, for beams with openings located at span quarter points (S/L=0.25), the drawback of opening presence on cracking and failure loads becomes significant at reinforcement ratios of 0.25μmax and 0.4μmax, respectively. Besides, this drawback becomes pronounced at lower reinforcement ratios for beams subjected to concentrated loads than for beams loaded uniformly. In addition, it is noticed that the reduction in cracking and failure loads for beams subject to concentrated load is higher than those for beams subject to uniform load particularly in case of beams with central opening. This is because for beams subject to concentrated load, the opening location is subject to higher shearing forces. In general, the increase in tension reinforcement ratio requires larger compression flange and, therefore, makes the beam more sensitive to opening presence.

Table 5 Cracking and failure loads for simply supported beams under uniform load (series F)

		Cracking load (kN/m)			Failure load (kN/m)		
Analyzed beams		Solid beams	Beams with central opening	Beams with opening located at S/L=0.25	Solid beams	Beams with central opening	Beams with opening located at S/L=0.25
Reinfo-rcement ratios	$\mu=0.25\mu_{max}$ (μ_{min})	24.5 (21.55)*	24.5	22.05	49.0 (44.91)*	49.0	49.0
	$\mu=0.4\mu_{max}$	60.8 (57.83)*	60.8	48.64	76.0 (71.67)*	76.0	76.0
	$\mu=0.5\mu_{max}$	65.8 (59.0)*	63.83	50.67	94.0 (89.7)*	94.0	83.66
	$\mu=\mu_{max}$	108.0 (104.5)*	81.0	59.4	180.0 (177.84)*	153.0	90.0

* Values calculated using (ECP-203)

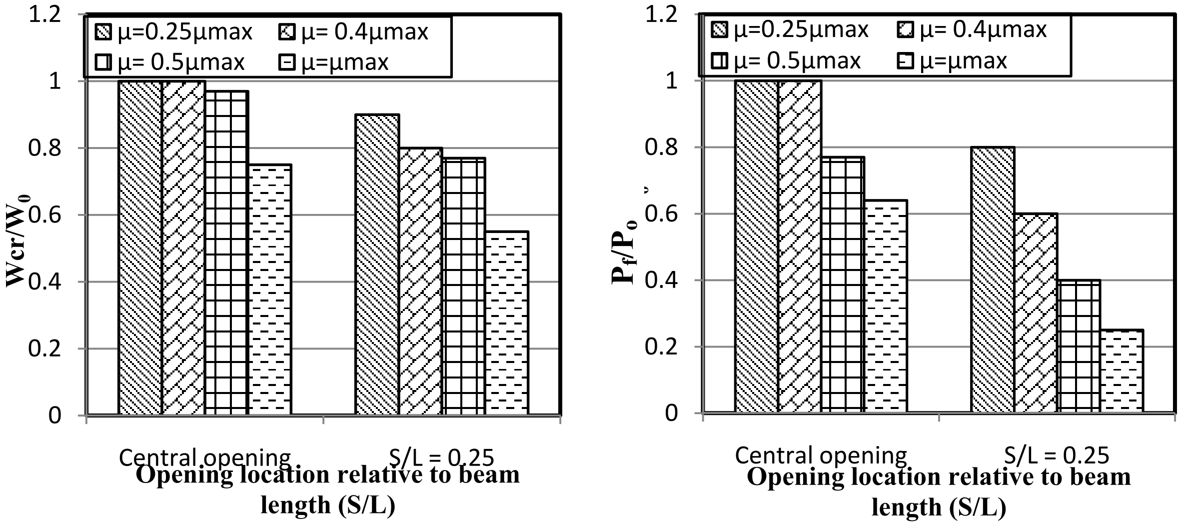
Table 6 Cracking and failure loads of simply supported beams under concentrated load (series G)

		Cracking load (kN)			Failure load (kN)		
Analyzed beams		Solid beams	Beams with central opening	Beams with opening located at S/L=0.25	Solid beams	Beams with central opening	Beams with opening located at S/L=0.25
Reinfo-rcement ratios	$\mu=0.25\mu_{max}$ (μ_{min})	33.41 (29.63)*	33.41	26.73	74.25 (70.86)*	74.25	74.25
	$\mu=0.4\mu_{max}$	80.33 (76.4)*	80.33	48.2	114.75 (112.5)*	114.75	80.33
	$\mu=0.5\mu_{max}$	72.0 (68.73)*	55.44	28.8	144.0 (140.55)*	144.0	86.4
	$\mu=\mu_{max}$	135.0 (131.6)*	86.4	33.75	270.0 (266.26)*	216.0	97.2

* Values calculated using (ECP-203)

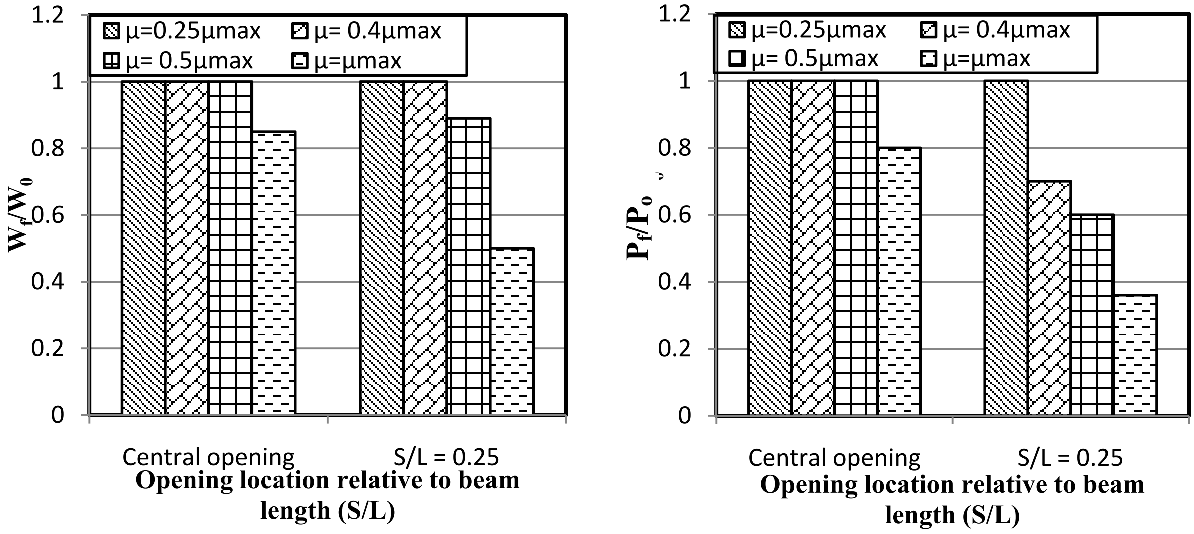
4.3.2 Continuous beams

Effect of the tension reinforcement ratio on cracking and failure loads of fixed-fixed beams is presented in Tables 7 & 8 together with Figs. 10 & 11. The behavior of fixed-fixed beams with varying tension reinforcement ratio is qualitatively similar to that of simply-supported ones since the increase in μ results in stronger detrimental effect of opening presence.



(a) Uniform load (series F) (b) Concentrated load (series G)

Fig. 8 Effect of reinforcement ratio (μ) on the relative cracking load of simply supported beams with L/D=5.8



(a) Uniform load (series F) (b) Concentrated load (series G)

Fig. 9 Effect of reinforcement ratio (μ) on the relative failure load of simply supported beams with L/D=5.8

Table 7 Cracking and failure loads of continuous beams under uniform load (series H)

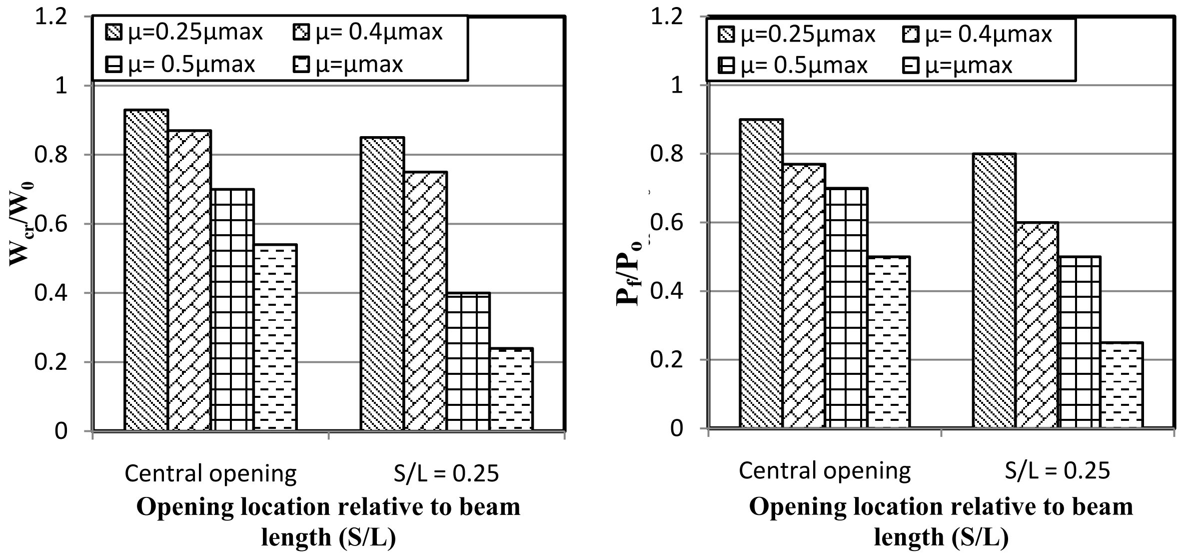
		Cracking load (kN/m)			Failure load (kN/m)		
Analyzed beams		Solid beams	Beams with central opening	Beams with opening located at S/L=0.25	Solid beams	Beams with central opening	Beams with opening located at S/L=0.25
Reinforcement ratios	$\mu=0.25\mu_{max}$ (μ_{min})	61.75 (55.2)*	57.43	48.81	95.0 (89.82)*	95.0	95.0
	$\mu=0.4\mu_{max}$	98.8 (94.67)*	85.96	74.1	152.0 (149.34)*	152.0	152.0
	$\mu=0.5\mu_{max}$	94.0 (90.3)*	65.8	37.6	188.0 (186.4)*	188.0	125.96
	$\mu=\mu_{max}$	144.0 (139.5)*	36.0	34.65	360.0 (356.68)*	280.8	216.0

* Values calculated using (ECP-203)

Table 8 Cracking and failure loads of continuous beams under concentrated load (series I)

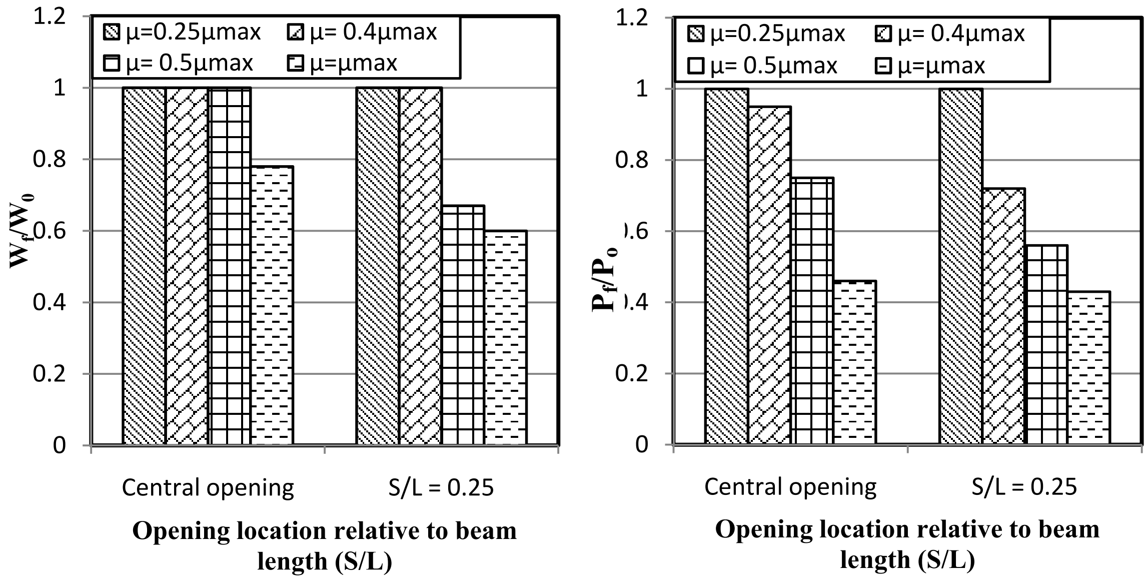
		Cracking load (kN)			Failure load (kN)		
Analyzed beams		Solid beams	Beams with central opening	Beams with opening located at S/L=0.25	Solid beams	Beams with central opening	Beams with opening located at S/L=0.25
Reinforcement ratios	$\mu=0.25\mu_{max}$ (μ_{min})	89.1 (85.22)*	80.19	71.28	148.5 (141.72)*	148.5	148.5
	$\mu=0.4\mu_{max}$	114.75 (100.56)*	88.36	68.85	229.5 (225.0)*	218.03	165.24
	$\mu=0.5\mu_{max}$	115.2 (101.8)*	80.64	57.6	288.0 (281.0)*	216.0	161.28
	$\mu=\mu_{max}$	189.0 (184.98)*	94.5	47.25	540.0 (536.26)*	248.4	232.2

* Values calculated using (ECP-203)



(a) Uniform load (series H) (b) Concentrated load (series I)

Fig. 10 Effect of reinforcement ratio (μ) on the relative cracking load of continuous beams



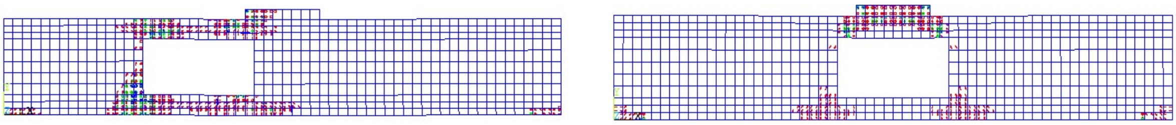
(a) Uniform load (series H) (b) Concentrated load (series I)

Fig. 11 Effect of reinforcement ratio (μ) on the relative failure load of continuous beams

4.4 Crack patterns and modes of failure

Crack patterns for beams with opening located at one quarter the span (S/L=0.25) and beams with central openings are shown in Figs. 12a and 12b, respectively, while the corresponding axial stress distributions are depicted in Figs. 13 and 14, respectively.

For beams with opening located at one quarter the span (S/L=0.25), referring to Fig. 12a, the first crack (diagonal shear crack) appeared at the external lowest corner of the opening near the support. This was followed by a crack at the opposite corner of the opening, and with increasing loads, cracks appeared at other corners. These cracks propagated from the beam end (shear critical zone) to the center of the opening. The failure mode of these beams is classified as shear. This is also verified by inspection of the longitudinal stress distribution in Fig. 13 where the chord members above and below the opening have stress distribution similar to the chords of a Vierendeel girder. Each chord is subject to tension and compression with the maximum stresses located at the top and bottom corners of the opening.



(a) Opening located at quarter span (b) Opening located at midspan

Fig. 12 Crack patterns at failure for simply supported beams with opening under concentrated load (series G)

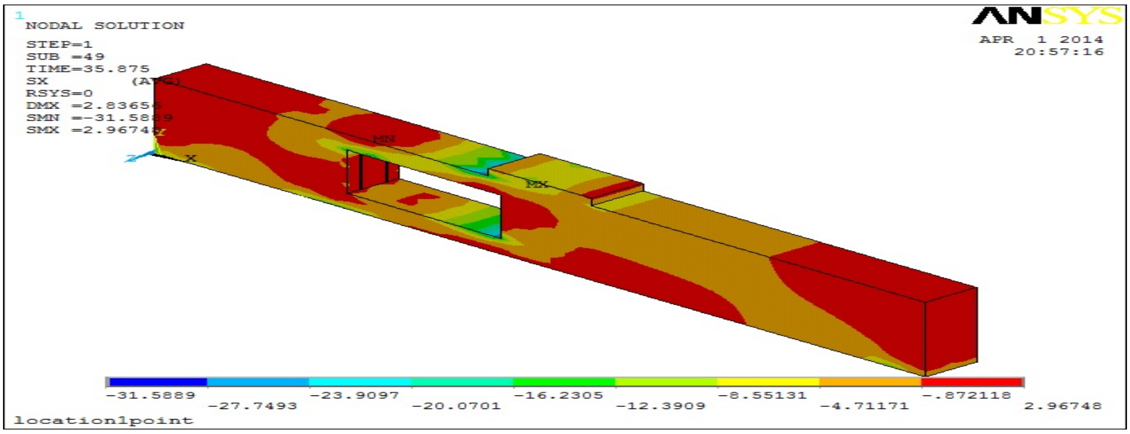


Fig. 13 Nodal SX stresses of beam with opening located at (S=0.25L) under concentrated load

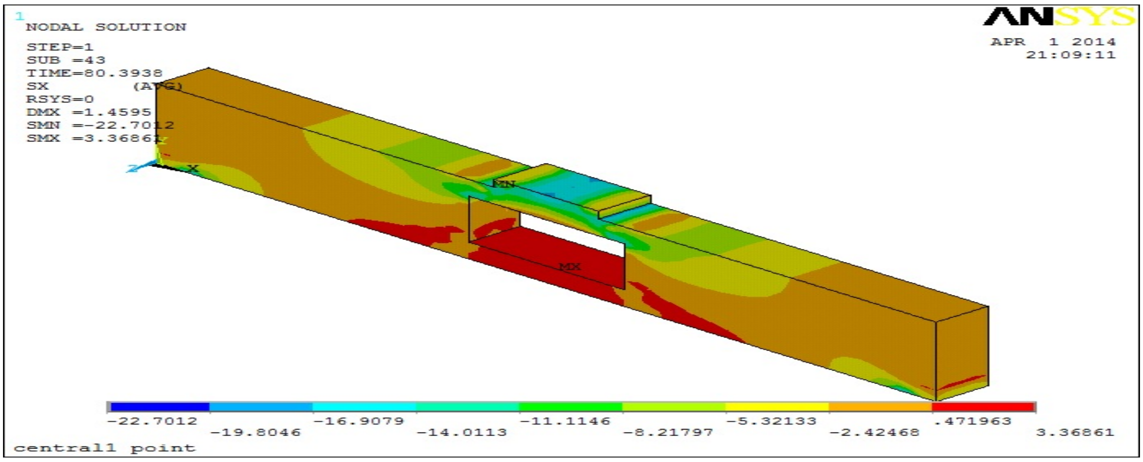
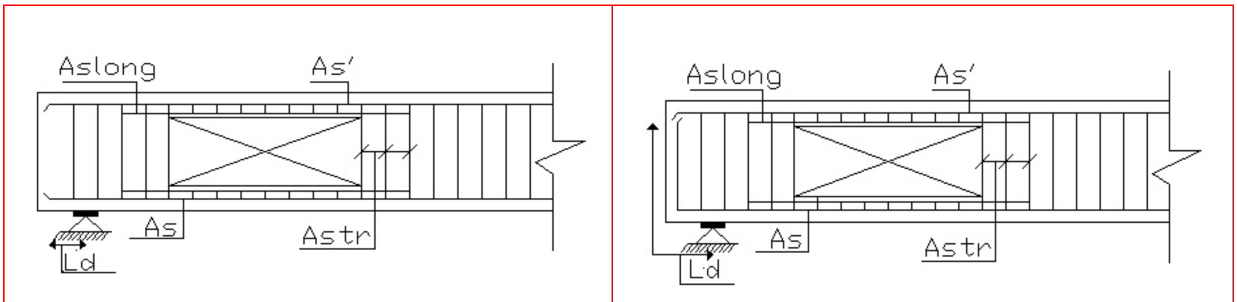


Fig. 14 Nodal SX stresses of beam with opening located at (S=0.50L) under concentrated load

For beams with central opening, Fig. 12b, the crack pattern was similar to that of beams without opening. The first "vertical" cracks appeared at the lower corners of the opening. Then, with increasing load, other flexural cracks appeared. These flexure cracks continued to propagate, and some switched into diagonal cracks until beam failure. Thus, failure mode of this beam is classified as flexural. Figure 14 confirms the flexure failure mode of this beam as the stress distribution is similar to that of solid beams where the top chord is subject to pure compressive stresses while the bottom chord is subject to pure tensile stresses.

4.5 Effect of tension reinforcement development at hinged support

To study the effect of tension reinforcement development condition at hinged support, simply supported beams with openings at span quarter points (S/L=0.25) are considered. Each beam is analyzed under a single concentrated load assuming different tension reinforcement ratios (μ= 0.25μmax, 0.4μmax, 0.5μmax, and μmax) and two reinforcement details as shown in Figs. 15a and 15b. Details (a) and (b) in these figures represent partially developed, and fully developed tension reinforcement, respectively. For these beams, Table 9 lists the failure loads while Table 10 presents the strains in tension reinforcement at failure. Table 9 shows that the failure load is higher in beams with detail (b) due to better utilization of reinforcement with full development. This is also inferred from Table 10 by the higher strains recorded in tension reinforcement of beams with detail (b) as compared to beams with detail (a). The results in Tables 9 and 10 highlight the importance of providing the tension reinforcement with sufficient development at hinged ends.



(a) Partially developed | (b) Fully developed

Fig. 15 Details of development condition of tension reinforcement at hinged support

Table 9 Failure loads of simply supported beams under concentrated load with openings located at span quarter point (S/L=0.25)

		Failure load (kN) for beams with		Ratio (2)/(1)
		(1) Detail (a)	(2) Detail (b)	
Reinforcement ratio	$\mu=0.25\mu_{max}$	74.25	74.25	1.00
	$\mu=0.4\mu_{max}$	80.33	114.75	1.43
	$\mu=0.5\mu_{max}$	86.4	119.62	1.39
	$\mu=\mu_{max}$	97.2	124.54	1.28

Table 10 Strains in tension reinforcement of simply supported beams with openings located at span quarter point (S/L=0.25) with detail (a) and detail (b) under concentrated load

		Strain in tension reinforcement for beams with	
		Detail (a)	Detail (b)
Reinforcement ratio	$\mu=0.25\mu_{max}$	0.0000122	0.000623
	$\mu=0.4\mu_{max}$	0.0000136	0.000695
	$\mu=0.5\mu_{max}$	0.0003420	0.001245
	$\mu=\mu_{max}$	0.001400	0.001751

5. CONCLUSIONS

Based on the review of published results as well as additional results obtained in this study, the following conclusions are drawn.

- The structural performance of beams with openings is affected by many factors like boundary conditions, shear span to depth ratio, opening size and locations, tension reinforcement ratio and development conditions, and type of applied load.
- For RC beams with central openings subjected to uniform load, the effect of opening presence can be ignored when the opening height ratio $h_0/D=0.20$, and the opening length ratio $L_0/L=0.05$, for any tension reinforcement ratio. The opening size limits reduce to $h_0/D=0.50$, and $L_0/L=0.20$, for tension reinforcement ratio not greater than $0.4\mu_{max}$.
- For other beam and opening conditions, presence of openings mandates advanced structural analysis and requires special reinforcement around the opening that may be in the form of: extra stirrups above and below the opening, extra stirrups at both sides of the opening, and longitudinal reinforcement in the top and bottom chords.
- Simplified and empirical design methods existing in some design codes and research publications may not be adequate for large openings with opening height ratio h_0/D of 0.50, opening length ratio of $L_0/L=0.20$, and for openings located near to the supports (high shear zone).
- In cases where simplified and empirical design methods fail, the finite element method and the strut and tie procedure offer an alternative practical solution.

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