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Effects of Transverse Circular Opening in Reinforced Concrete Beam Subjected to Incremental Static Load

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Abstract: This paper presents an experimental study to investigate the effects of circular transverse opening in the reinforced concrete beam. Understanding its behaviour would allow such beams to be safely used, particularly for the passage of pipes and ducting. A total of eleven beams with a cross-sectional area of 150 mm x 300 mm and a clear span of 1500 mm were tested under four-point load setup until failure. This comprised two beams without opening as the control beams, six beams with an opening (50 mm, 75 mm and 100 mm in diameter) positioned at the mid-span and near to the support, and three beams with the reinforcement at the opening. The effects of the opening size, the position of the opening and different reinforcing methods on beam performance were studied. The beam failed with severe cracking surrounding the opening. The test results showed that the opening affected the ultimate strength and ductility of the beam. For the beam without reinforcement at the opening to maintain 80% strength, the opening size should not exceed 0.25 times the beam's height. The diagonal bar reinforcing method was found effective in reinforcing the opening not exceeding 1/3 of beam height.

Keywords: Reinforced Concrete Beam, Circular Transverse Opening, Flexural and Shear Load.

INTRODUCTION

Transverse opening in the reinforced concrete beam is sometimes inevitable, especially when there is limited ceiling space under the beam. It allows pipes and ducting to pass through a beam.

However, to some extent, it affects the structural performance of a beam. Beams with transverse opening normally (a) have lower strength and stiffness, (b) endure an excessive deflection, and (c) experience premature cracking and failure [1-7]. This is mainly attributed to the concentration of stress surrounding the opening as a result of the discontinuity of the cross-sectional configuration [2].

Such negative effects magnify as the opening size increases [8, 9], and when it is positioned at the shear zone of the beam [10]. The circular opening is normally preferred due to inexistence of sharp edges and corners where the concentration of high stress occurs [10, 11].

The questions are (a) to which extent the transverse opening affects the beam's performance, (b) what is the allowable size of opening without requiring additional reinforcement, (c) where is the best location for the opening, and (d) should additional reinforcement is provided, how it is effectively done?

For that, an experimental study was carried out to investigate the behaviour of reinforced concrete beams having a circular opening when subjected to load.

MATERIALS AND METHODS

Specimen Details

Eleven (11) beam specimens were fabricated and tested under the four-point load test (Figure 1). The specimens comprised 2 control beams without opening, 6 beams with an opening, and 3 beams with opening and with opening reinforcements (Table 1). The beam dimension was 150 mm x 300 mm and 1650 mm. The clear span between supports was 1500 mm.

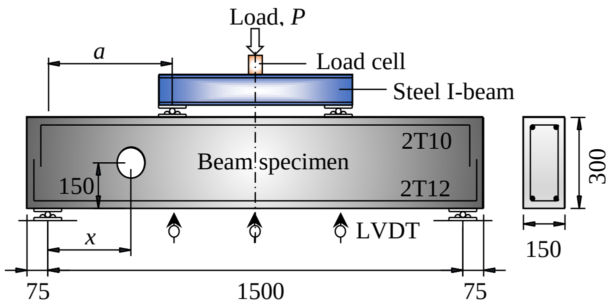

Figure 1: Test setup (dimension in mm)

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All specimens were reinforced with 2T12 and 2T10 high yield steel bars (nominal yield strength, $f_{y,b}$ = 460 N/mm^2) as the bottom and top reinforcements, respectively. The shear links provided were R8-150 and R8-250 mild steel bars (nominal yield strength, $f_{y,sl}$ = 250 N/mm^2) for flexural and shear load tests, respectively. The concrete cover was 25 mm throughout the beam.

Table 1: Specimen details (Refer to Figure 1)

Specimen	*d* *(mm)*	*x* *(mm)*	*a* (mm)	Stirrup
C1/S	-	-	500	R8-250
C2/F	-	-	600	R8-150
S1/100	100	300	500	R8-250
S2/75	75	300	500	R8-250
S3/50	50	300	500	R8-250
F1/100	100	750	600	R8-150
F2/75	75	750	600	R8-150
F3/50	50	750	600	R8-150
R1/DR	100	300	500	R8-250
R2/GI	100	300	500	R8-250
R3DS	100	300	500	R8-250

^{1}C – control, S – shear, F – flexural, R – reinforcement to opening

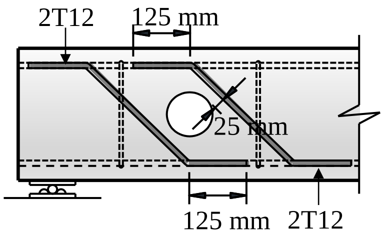
The beam specimens were cast in a horizontal position using plywood moulds. Ready-mixed concrete grade 25 was used. The maximum aggregate size was 20 mm and the designed slump was 60 mm – 180 mm. The specimens were cured for at least 7 days at a temperature of 30 ± 5°C and tested after 28 days of casting.

One transverse opening made of Polyvinyl Chloride (PVC) pipe was placed at the mid-height of the beam (150 mm from soffit), and an *x* distance from the support as given in Table 1 (Figure 1). The size varied from 50 mm to 100 mm, and it was placed at two locations; at the mid-span, and near the support.

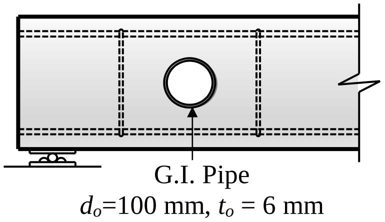
Three types of reinforcing method for the opening under the shear load were proposed, namely diagonal bar, G.I. pipe and diagonal square reinforcing methods (Figure 2). The reinforcement bars were placed at 25 mm offset distance from the transverse opening. The G.I. pipe was used to replace the PVC pipe for higher compressive strength of the transverse opening. The effectiveness of these reinforcing methods to restore the beam's strength was evaluated.

Test setup

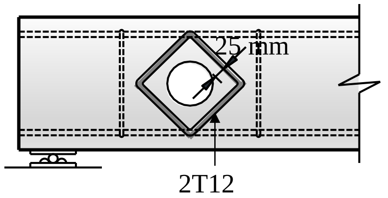
To test the specimens, a static load was applied at the mid-span. The steel I-beam distributed the load into 2 point loads acting on the beam. A load cell was placed between the hydraulic cylinder and the steel I-beam to measure the applied load. Three linear variable differential transducers (LVDT) were placed at the beam soffit at mid-span and below the 2 point loads to measure the deflection of the beam. All measuring devices were connected to a data logger for data acquisition. The specifications of the instruments used are outlined in Table 2.



(a) R1/DR: Diagonal bar



(b) R2/GI: G.I. Pipe



(c) R3/DS: Diagonal square

Figure 2: Proposed reinforcing methods for opening

Table 2: Instrument specifications

Instruments	Brand, Model	Description	Data accuracy
Hydraulic Cylinder	Enerpac, RR-10018	Push +933 kN Pull -435 kN	-
Hydraulic Pump	Enerpac P464	Manual hand pump	-
Displacement transducer	TML, CDP-100	100 mm	0.01 mm
Load Cell	TML, CLJ-300KNB	Capacity 300 kN	0.01 kN
Data Logger	TML, TDS-530	30 Channels	-

Test procedure

Before the test started, all readings were set to zero. The beam was preloaded at not more than 10% the estimated beam capacity for about 5 minutes to consolidate the test setup. The load was then released for another 5 minutes to observe the reading recovered to about zero to cross-check the validity of the measuring devices. This process was repeated twice.

Next, the readings were re-initialised to zero and the test started. The load was progressively increased at the interval of either 7 kN load or 0.5 mm beam deflection, whichever reached first, until the specimen failed.

Readings were taken after holding the load for at least 1 minute. The propagation of cracks was monitored throughout the test.

RESULTS AND DISCUSSION

Material properties

Tables 3 and 4 show the properties of materials used to fabricate the specimens. A 150 mm concrete cube was tested on the testing day of the beam specimen to represent its concrete strength. The compressive strength and the density of concrete were quite consistent, and the tensile strength of the steel bars was consistently higher than their nominal strengths of 460 N/mm^2 and 250 N/mm^2. For that, the quality of the materials is considered acceptable.

Table 3: Properties of concrete

Testing day	Specimen*	Compressive strength, $f_{c,u}$ (N/mm^2)	Density, ρ_c (kg/m^3)
28	C1/S	25.1	2320
29	C2/F	25.9	2329
30	S1/100	24.7	2320
31	S2/75	24.9	2367
35	S3/50	25.4	2344
36	F1/100	25.7	2329
37	F2/75	25.0	2347
38	F3/50	26.9	2335
42	R1/DR	26.7	2367
43	R2/GI	26.2	2320
44	R3/DS	25.8	2373

Table 4: Tensile strength of steel

Bar type	Tensile strength, $f_{s,u}$ (N/mm^2)			Average strength, (N/mm^2)
	T1	T2	T3	
High yield steel bar	532	551	547	543
Mild steel bar	295	281	278	285

Test results

The test results of the specimens are summarized in Table 5.

The observed results include (a) the loads when the shear and flexural cracks were first detected, and (b) the load when the cracks first reached the opening. These results were obtained from the markings made during the experimental test that demonstrated the propagation of cracks at various load levels.

The measured results comprise the data obtained directly from the measuring instruments. This included the ultimate load and displacements.

The computed results translate the loads acting on the beam specimens into the equivalent bending moment and shear load (Eqs. 1 and 2). These loads were derived from the free-body diagrams illustrated in Figure 3. The beam's weight was considered as a uniformly distributed load.

$$V = \frac{P}{2} + \frac{w_{sw}l}{2} \qquad (1)$$

$$M = \frac{1}{2}\left(Pa + \frac{w_{sw}l^2}{4}\right) \qquad (2)$$

where w_{sw} = self-weight of beam
γ_c = unit weight of concrete

Table 5: Test results of beam specimens

Specimen	Observed results				Measured results		Computed Results			
							Frist crack		Ultimate state	
	First shear crack, $P_{ic,s}$ (kN)	First flexural crack, $P_{ic,f}$ (kN)	Crack reached opening, $P_{ic,o}$ (kN)	Failure mode $*^1$	Ultimate load, P_u (kN)	Displacement, $\delta_{2,u}$ (mm)	Load, P_{ic} $*^2$	Moment , M_{ic} (kNm)	Shear load, V_u (kN)	Moment , M_u (kNm)
C1/S	96	47	-	F	163.1	10.20	47	12.1	82.4	41.1
C2/F	34	34	-	F	156.8	10.42	34	10.5	79.2	47.4
S1/100	44	39	46	S	108.0	5.76	39	10.1	54.8	27.3
S2/75	69	38	70	S	126.7	6.99	38	9.8	64.2	32.0
S3/50	85	30	126	S	135.8	9.34	30	7.8	68.7	34.3
F1/100	40	33	40	F/S	102.3	8.61	33	10.2	52.0	31.0
F2/75	50	39	125	F/S	127.2	8.30	39	12.0	64.4	38.5
F3/50	69	30	44	F/S	134.3	10.07	30	9.3	68.0	40.6
R1/DR	52	40	89	F	141.1	17.65	40	10.3	71.4	35.6
R2/GI	53	43	71	S	101.6	7.89	43	11.1	51.6	25.7
R3/DS	54	32	81	S	119.0	9.59	32	8.3	60.3	30.1

*Note: ^1F – flexural failure, S – shear failure, F/S – flexural and shear failure, $^2P_{ic} = \min\left(P_{ic,s}, P_{ic,f}\right)$

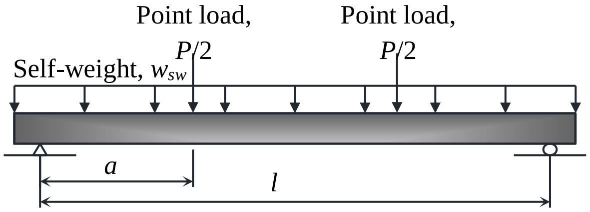


Figure 3: Free-body diagram for test setup

Table 5 shows that:

a. The flexural cracks usually developed first and followed by the shear cracks. $P_{ic,f}$ was always lower than $P_{ic,s}$.
b. The propagation of the first flexural crack was not noticeably influenced by the size, location, and reinforcing method. It occurred at an average moment load of about 9.9 kNm.
c. The opening affects the performance of the beam more significantly as the opening size increased. When the size decreased from 100 mm to 50 mm,
    - The occurrence of the first shear crack delayed.
    - The crack reached the opening slower when subjected to shear load. No delay was noticed under the flexural load
    - The ultimate capacity of the beam increased.
    - The beam endured a larger ultimate displacement.

Reinforcements at the opening led to:

a. About 20% increase of the load to initiate the shear crack.
b. 54% to 93% increase in the load for the crack to reach the opening.
c. Diagonal bar reinforcing method (specimen R1/DR) was the most effective among all in strengthening the beam. It controlled the propagation of cracks surrounding the opening and increased the shear capacity by 30%.
d. G. I. pipe did not contribute to strengthening the beam with opening.

Load-Displacement Response

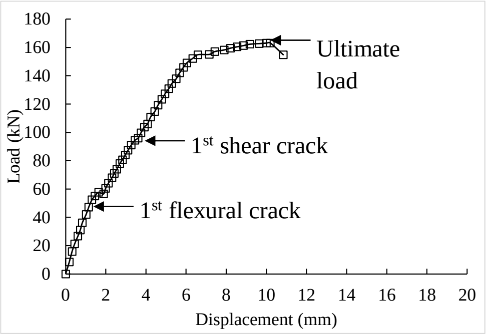
Figure 4(a) shows the load-displacement response of a solid beam. It initiated with a high degree of stiffness, as represented by the slope of the load-displacement curves. While the beam was in the elastic stage, it deflected slightly and about proportionally to the applied load.

Then, the first crack developed at the mid-span as a flexural crack. It initiated from the beam’s soffit and propagated upward. This affected the stiffness slightly. As the load increased, (a) the cracks widened and propagated further, (b) more cracks were observed, and (c) the cracking regions expanded sideways from the mid-span toward the supports at both ends until a diagonal shear crack developed. The stiffness gradually deteriorated as the number of cracks increased, and hence, the deflection developed at a faster rate.

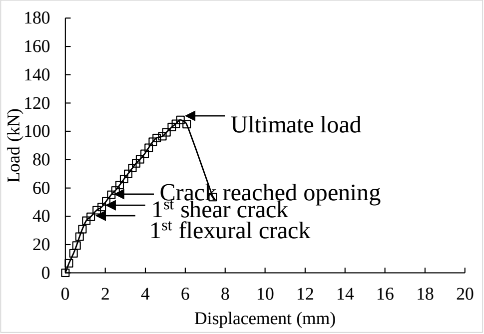
Then, the beams yielded due to excessive cracking of concrete and excessive deformation or yielding of the tension bars in the beam. As the bars lost the bonding with concrete, the deflection accelerated and the stiffness dropped drastically until critical damage occurred.

By then, the load resistance of the beam had peaked and the ultimate state was reached. Beyond that, the beam lost integrity and was considered failed.

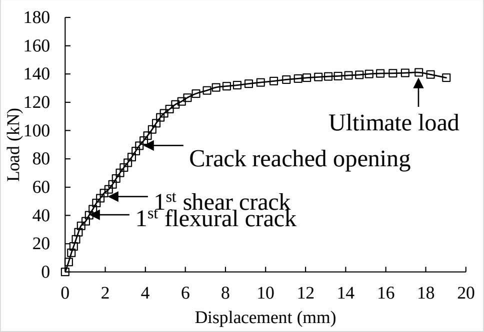
Figures 4(a), (b) and (c) compares the typical load-displacement responses of the control beam, beam with opening, and beam with opening and with reinforcement.



(a) Specimen C1/S



(b) Specimen S1/100



(c) Specimen R1/DR

Figure 4: Load-displacement

In general, the beam with opening exhibited a lower stiffness, first shear crack, yield strength, ultimate strength, and ductility compared with the solid beam. It failed almost immediately after its yield point.

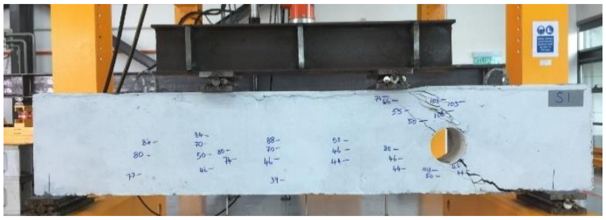
If adequately reinforced, as demonstrated by the diagonal bar reinforcing method, the beam with opening would have comparable ultimate strength to the solid beam. The reinforcement delayed the propagation of the first shear crack, prolonged the post-yielding stage of the beam and notably improved the ductility of the beam. However, it did not impose much effect on the stiffness.

Ineffective reinforcing methods, such as G. I. pipe and diagonal square reinforcing methods, resulted in a slightly better performance than without reinforcement, but inferior to the diagonal bar reinforcing method.

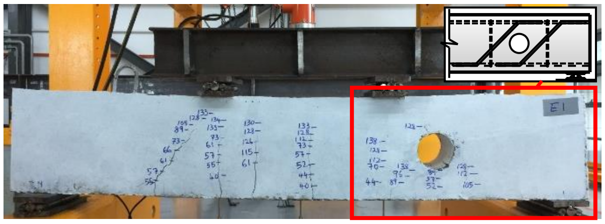
Failure mode

Figure 5 compares the crack patterns of the control beam, the beam with opening, and the beam with opening and with reinforcement.

(a) Specimen C1/S



(b) Specimen S1/100



(c) Specimen R1/DR

Figure 5: Crack patterns of test specimen

In general, dense and severe cracks were observed surrounding the opening (Figure 5(b)). A large diagonal shear crack was observed propagating from the support, passing through the opening and toward the point load. The crack was believed to be the critical cause of failure that weakened the beam.

The diagonal bars managed to control the propagation of the shear crack, and as a result, the cracks surrounding the opening were not as dense and severe compared with beam without reinforcement (Figure 5(c)).

Effects of opening to Reinforced Concrete Beam

Table 6 compares the performance of the beam with opening with respect to the control beam. It demonstrates the effects of opening to reinforced concrete beam.

Table 6: Performance of beams with opening relative to control beam

Effects of:	Specimen	Ultimate strength $P_{u,i}/P_{u,c}$	Ultimate displacement $\delta_{u,i}/\delta_{u,c}$
Opening near the support	C1/S	1.00	1.00
	S1/100	0.67	0.56
	S2/75	0.78	0.69
	S3/50	0.83	0.92
Opening at mid-span	C2/F	1.00	1.00
	F1/100	0.66	0.83
	F2/75	0.81	0.80
	F3/50	0.86	0.97
Reinforcing method for opening	S1/100	1.00	1.00
	R1/DR	1.30	3.06
	R2/GI	0.94	1.37
	R3/DS	1.10	1.66

Note: $P_{u,i}$ and $\delta_{u,i}$ are the ultimate strength and displacement of the test specimen respectively, meanwhile, $P_{u,c}$ and $\delta_{u,c}$ represent the control specimen.

In terms of ultimate strength, it is observed that:

a. The opening affected the ultimate strength of the beam, regardless of its position at the mid-span or near to the support. The $P_{u,i}/P_{u,c}$ ratio were always less than 1.0.
b. Such detrimental effects amplified as the opening size increased. The $P_{u,i}/P_{u,c}$ ratio reduced as the opening size increased from 50 mm to 100 mm.
c. The opening affected the beam's strength more significantly at the support than the mid-span. The $P_{u,i}/P_{u,c}$ ratio of the beam with opening near the support were generally lower than at the mid-span.
d. The beam strength deteriorated at about the same rate, for beams with opening near to support and mid-span, as the opening size increased. It can be observed from the rate of reduction in terms of $P_{u,i}/P_{u,c}$ ratio of the two sets of specimens.

The ultimate displacement governed the ductility response of the beam. It is seen that

a. The opening affected the ductility of the beam. The $\delta_{u,i}/\delta_{u,c}$ ratio were always less than 1.0.
b. The ductility was more significantly affected when the opening is placed closer to the support. The $\delta_{u,i}/\delta_{u,c}$ ratios of such beams were consistently lower than those placed at the mid-span.
c. The ductility was more significantly affected as the opening size increased, as observed from the reduction of the $\delta_{u,i}/\delta_{u,c}$ ratios. The ratio reduced at

a faster rate when the opening was near to the support.

The transverse opening imposed detrimental effects on beam opening performance, particularly in terms of the strength and ductility. The larger the opening size the structural performance was more remarkably affected. It was more critical when the opening was placed near to the support.

For a beam with opening to maintain at least 80% of its strength without providing additional reinforcement for the opening, the opening size should not exceed about 75 mm, which was equivalent to 0.25*h*. This is in-line with the findings by Somes and Corley (1974) [8].

Table 6 also compared the effectiveness of the three reinforcing methods proposed. Diagonal bar reinforcing method (R1/DR) was found most effective offering 30% higher strength and 3 times larger deflection compared with the beam without reinforcement. G.I. reinforcing method (R2/GI) is the least effective, as the beam performance was about similar to the beam without reinforcement. The diagonal square reinforcing method (R3/DS) managed to increase only 10% of the strength of the unreinforced beam.

Based on these observations, the following principles can be extracted:

a. Strengthening the circular opening to resist deformation (e.g. using G.I. pipe) offers no meaningful strengthening effect to bending resistance of a beam.
b. Reinforcement should be provided in the manner of intercepting the propagation of the diagonal shear crack, and the reinforcing bars should be aligned perpendicularly to the direction of the crack to yield the best performance.
c. The reinforcing bars should cover a wider region surrounding the opening to prevent the crack to reroute and bypass it, as experienced by the diagonal square reinforcing method.

CONCLUSION

The transverse opening affects the ultimate strength and ductility of a reinforced concrete beam. Such detrimental effect is more pronounced as the opening size increases. Without reinforcement at the opening, the opening size should not exceed 0.25 times the beam’s height, so that the beam maintain at least 80% of its strength. The opening is preferably placed at the region with low shear load, which is at the mid-span, so that the ductility of the beam is not adversely affected. The opening can be reinforced by using diagonal bars. This reinforcing method could restore the beam’s strength as per a solid beam.

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