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Comparison between Modelling and Experimental Behaviour of Reinforced Concrete Beam with Transverse Circular Opening

Jen Hua Ling, Wen Yue Pao, Wen Kam Leong and How Teck Sia

School of Engineering and Technology, University College of Technology Sarawak (UCTS), 96000 Sibu, Sarawak, Malaysia

Abstract: In this study, a finite element model was developed with the aid of a computer program, Ansys, to predict the behaviour of reinforced concrete beams with transverse openings under load. This method is more economical and less time consuming than conducting experimental tests, provided it can reliably predict the actual response of the beam. To determine the reliability of the model, an analysis was carried out on the results produced by the model. The predicted results were compared with the experimental results in terms of the load-displacement responses, the mechanical properties, and the parametric responses. The model was unable to reliably predict the entire response of the beam, particular during the elastic and yielding stages of the beam. Nevertheless, it predicted the ultimate state of the beam (e.g. ultimate capacity and total deformation) with a 75% reliability. Should be model be used for further research studies or industrial applications, it should be used with cautions.

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

INTRODUCTION

Transverse opening is normally provided in a reinforced concrete beam when there is limited ceiling space underneath the beam for the crossing of building services like pipes and ducts. Instead of crossing underneath, it allows the services to pass through the beam.

The opening changes the cross-sectional configuration of a beam, and hence, alters its behaviour [1]. It disrupts the flow of stress within a beam and leads to the concentration of stress surrounding it [2, 3]. Thus, such beams generally have a lower strength, stiffness, and ductility than the normal RC beam [2, 4-9].

The beam performance was found affected by the number, size, shape, and position of the opening. For a higher strength of a beam, the opening should be (a) small [10-11], (b) without any sharp edge [12-14], and (c) placed at the low shear region [15].

The behaviour of beams with transverse openings is rather complex [1]. It is difficult to accurately predict its response through the derivation of equations. The actual response is normally acquired through experimental tests, which is rather costly and time-consuming.

Alternatively, it can be simulated through numerical modelling. This is provided the model can reliably predict the response of the beam. Otherwise, designing based on the simulated results can be quite dangerous.

In this study, a finite element model was developed with the aid of a computer program, Ansys, to simulate an experimental test conducted by Tang (2018) [16, 17] on reinforced concrete beams with circular transverse openings under load. The model was compared with the experimental results to determine its reliability.

MATERIALS AND METHODS

Specimen Details

A finite element model was used to simulate a four-point load test conducted on 8 reinforced concrete beam specimens, comprising 2 solid beams, 3 beams with openings at the support, and another 3 at the mid-span.

The details of the beam are: (Figure 1)

Dimension	: 150 mm x 300 mm x 1650 mm
Clear span	: 1500 mm
Reinforcements	: Top bars, 2T10
	: Bottom bars, 2T12
	: Stirrup, R8 – 250 or 150
Concrete cover	: 25 mm (all sides)

Corresponding Author: Jen Hua Ling. University College of Technology Sarawak (UCTS), Email: lingjenhua@ucts.edu.my

The position, *x*, and size, *d*, of the opening, the position of the point load, *a*, and the shear reinforcement of each specimen are given in Table 1

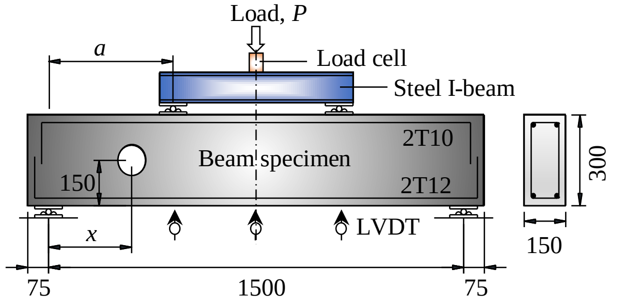


Figure 1: Test setup (dimension in mm) [17]

Table 1: Specimen details (Refer to Figure 1) [17]

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

[1]*C – control, S – shear, F – flexural*

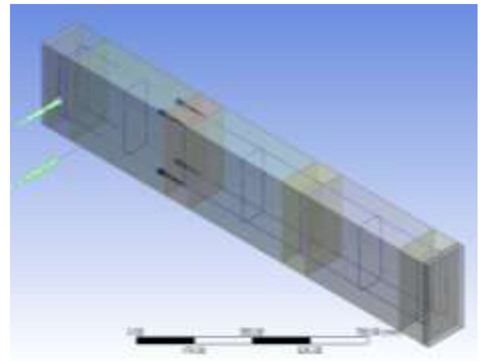
The material properties of the model are given in Table 2. The model ignored the Polyvinyl Chloride (PVC) pipe used to create the transverse opening in the beam. It was assumed contributing no strength to the beam.

Table 2: Material properties of the model

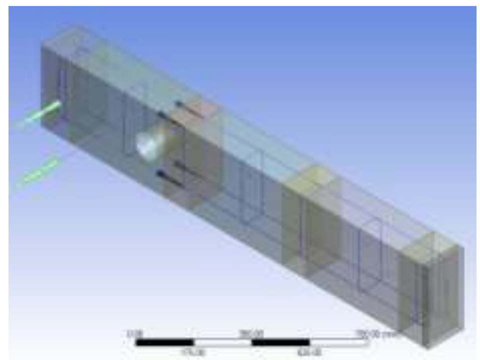
	Concrete	Rebar	Stirrup
Element	Solid65	Link180	Link180
Young modulus, E (N/mm^2)	24,000	200,000	200,000
Poisson ratio	0.2	0.3	0.3
Density, ρ (kg/m^3)	2400	7850	7850
Specified tensle yield strength, f_y (N/mm^2)	-	500	250
Compressive strength, f_c (N/mm^2)	25	-	-

Figure 2 shows the typical models of the beams with and without opening in Ansys. Rectangle and line geometries were assigned to represent the concrete beam and steel reinforcements, respectively.

The tetrahedron meshing was used (Figure 3). The meshing size was determined after several trails until the predicted results were (a) reaching constant values and (b) close to the experimental results, as given in Table 3

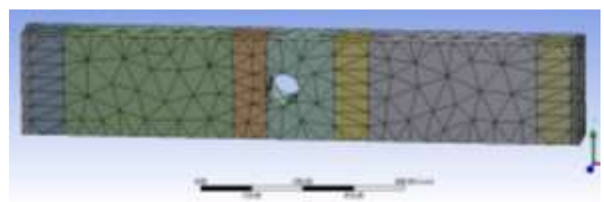


(a) Beam without opening (C1/S)



(b) Beam without opening (S1/100)

Figure 2 Typical beam models



(a) Meshing of concrete beam (43 mm)

(b) Meshing of reinforcement (2 mm)

Figure 3 Meshing of beam model

Table 3: Meshing size of each specimen (mm)

Specimen	Concrete	Rebar
C1/S	60	1
C2/F	60	1
S1/100	33	1
S2/75	32	2
S3/50	40	1
F1/100	43	2
F2/75	60	3
F3/50	58	3

In Ansys, the applied load was progressively increased and the computed beam deformation was recorded. The beam was considered failed when (a) Ansys presented an illogical shape of the beam, or (b) an unrealistically large deflection was obtained (Figure 4).

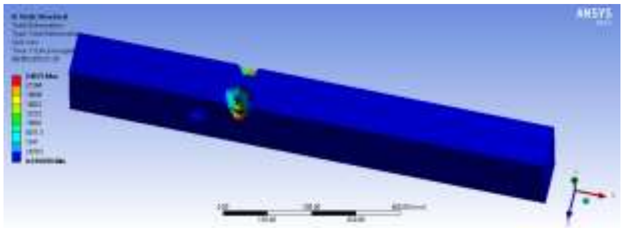


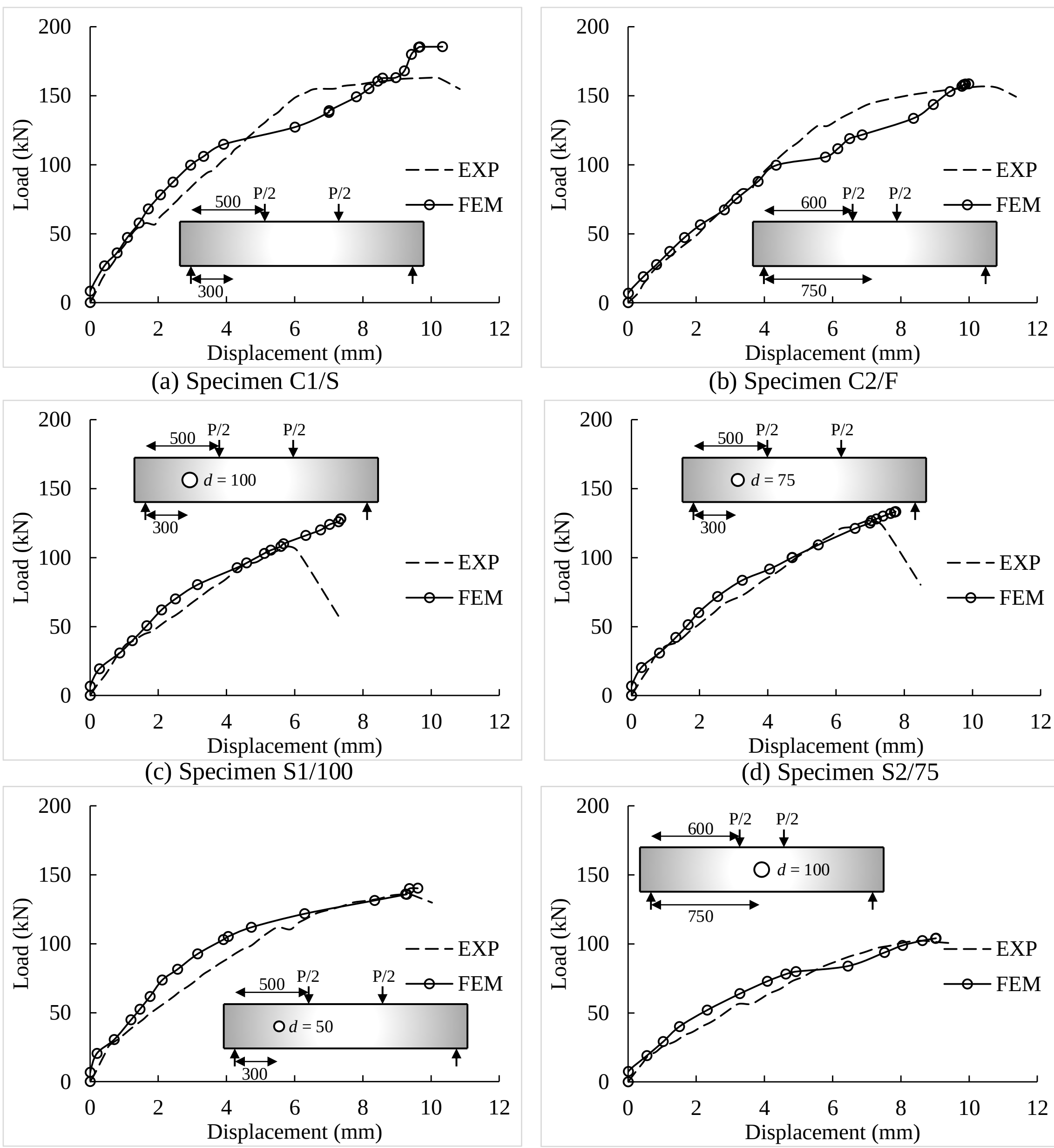
Figure 4: Failure of beam in Ansys

RESULTS AND DISCUSSION

The response simulated by the model were validated against the experimental results in terms of (a) load-displacement response, (b) mechanical properties, and (c) parametric response.

Load-displacement response

Figure 5 compares the load-displacement (*P*-*δ*) responses of the model and the experimental test. Both curves were quite close to each other. However, their trend (Figures 6(a) and (b)) and deflection (Figure 6(c)) varied.



(a) Specimen C1/S

(b) Specimen C2/F

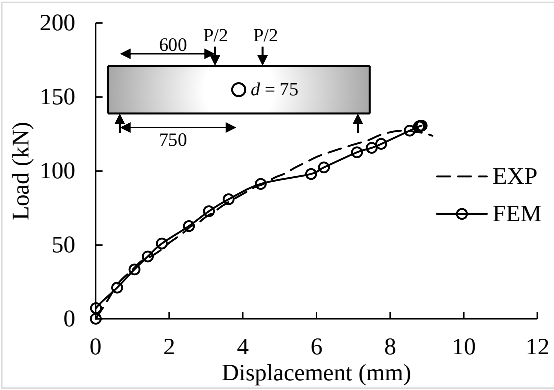
(c) Specimen S1/100

(d) Specimen S2/75

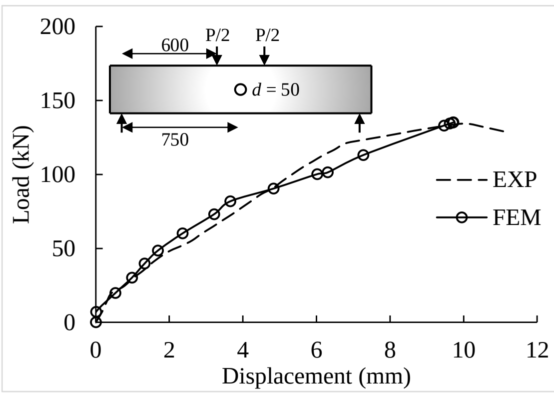
(e) Specimen S3/50

(f) Specimen F1/100

Figure 5: Comparison of the modelled and experimental load-displacement responses



(g) Specimen F2/75



(h) Specimen F3/50

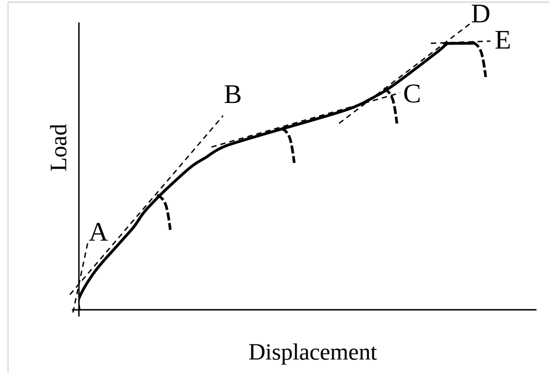
Figure 5: Comparison of the modelled and experimental load-displacement responses (Cont.)

From Figure 6(a), the model predicted the beam to response in 5 stages. It initiated with high stiffness in Stage A, as represented by the gradient of the curves. Then, the stiffness decreased progressively in Stages B and C, regained slightly in Stage D, and eventually, drastically decreased in Stage E. The beam may fail at any stage depending on its capacity (Figure 5).

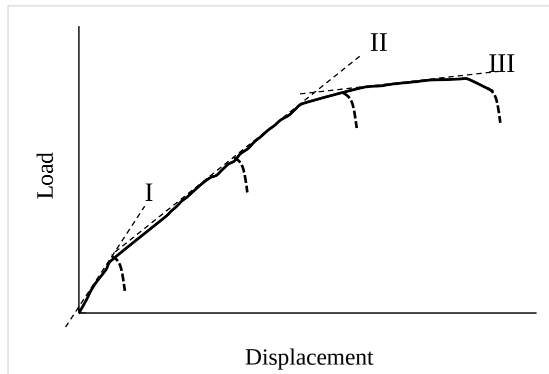
In the experiment, the beam underwent 3 stages (Figure 6(b)). It possessed a high stiffness in Stage I, and progressively decreased in Stages II and III. According to Ling et. al (2019) [17], the beam cracked, yielded and failed at the end of Stages I, II and III, respectively.

The predicted deflection deferred slightly from the experimental test (Figure 6(c)). Initially, the model predicted a slower development of deflection. At Point "i", it outran the experimental results, and then, being overtaken again by the experimental results at Point "ii".

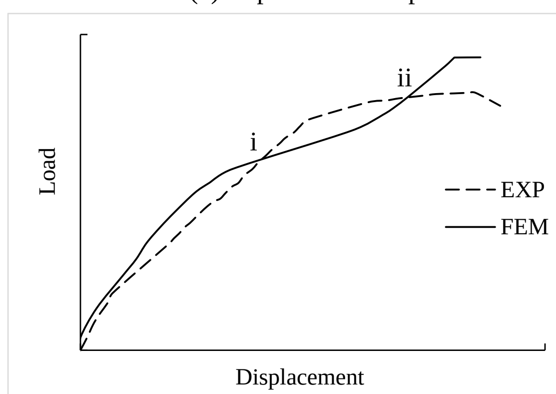
From Figure 5, the points "i" and "ii" generally occurred around 100 kN and 120 kN, respectively. A larger variation of deflection was found in the solid beam and the beams with a smaller opening. This implied that the model was less accurate in predicting the solid beams and the beams closely resembled the solid beams.



(a) FEM response



(b) Experimental response



(c) Combined response

Figure 6: Typical load-displacement response

Mechanical properties

Figure 7 demonstrates the computation of the mechanical properties of the beam from the P-δ curves. The highest point of the curve was the ultimate capacity of the beam, P_u. The corresponding value on the x-axis was the total displacement of the beam, δ_u.

Two horizontal lines were then drawn at the point P_u and 0.75 times P_u. The $0.75P_u$ line intercepted the P-δ curve at Point "A". A straight line was drawn from the Origin "O" to Point "A" and extended to intercept with the P_u line at Point "B" (Figure 7). The yield point (Point

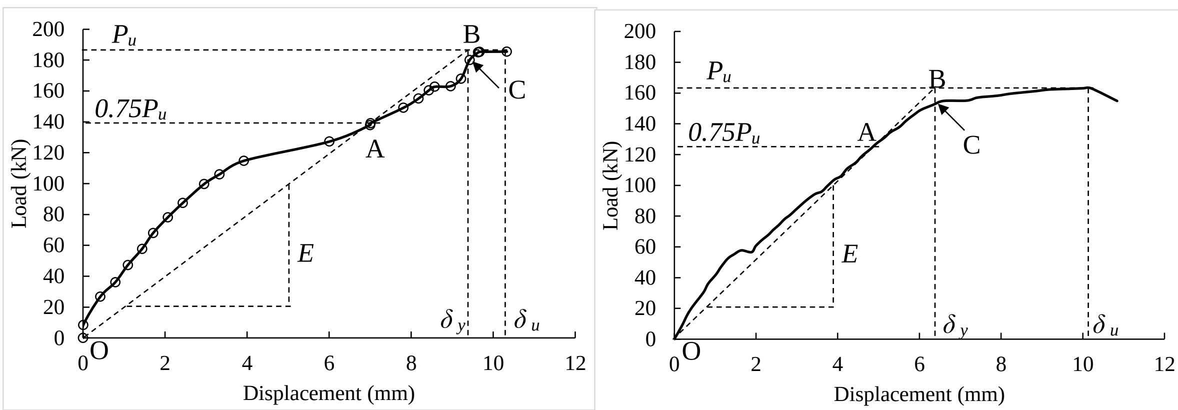
"C") on the P-δ curve just below Point "B". The secant stiffness, E, would be the gradient of the line OA.

The predicted results were then compared with the experimental results. The predicted results were considered reliable when (a) the variation between the two results were within ±10%, and (b) a majority of the specimens (≥80%) fulfilled the criteria.

For that, a reliability ratio, R_r, was computed by dividing the predicted results by the experimental results (Table 4). The ratio ranging from 0.9 to 1.1 represented a satisfactory prediction, and the percentage of satisfactory prediction should be more than 80% to signify a reliable prediction of a mechanical property of beam.

From Table 4, it is observed that:

- The model was unable to reliably predict the mechanical properties of the beam. None of the properties reached 80% satisfactory prediction.
- Nevertheless, the model could predict the strength properties and the ultimate state of the beam (i.e. yield strength, P_y, ultimate strength, P_u, and total deflection, δ_u) at a higher degree of reliability compared with the other properties like the secant stiffness and the ductility.
- The secant stiffness predicted was generally lower than the experimental results. This affected the accuracy of the prediction of the yield deflection, δ_y, and subsequently the ductility, Δ, of the beam.



(a) FEM model (b) Experimental test

Figure 7: Computation of mechanical properties from the P-δ curves of specimen C1/S

Table 4: Mechanical properties of specimens based on the predicted and experimental results

Specimen	Secant stiffness, E (kN/mm)				Yield strength, P_y (kN)				Yield deflection, δ_y (mm)			
	FEM	EXP	R_r	State	FEM	EXP	R_r	State	FEM	EXP	R_r	State
C1-S	19.8	25.8	0.77	NA	176.9	152.2	1.16	NA	9.37	6.32	1.48	NA
C2-F	18.3	23.3	0.79	NA	138.8	140	0.99	A	8.67	6.73	1.29	NA
S1-100	20.9	21.4	0.98	A	114.2	99.1	1.15	NA	6.13	5.05	1.21	NA
S2-75	21.2	20.7	1.02	A	118.1	120.7	0.98	A	6.29	6.12	1.03	A
S3-50	26.0	20.8	1.25	NA	116.1	120.7	0.96	A	5.39	6.53	0.83	NA
F1-100	16.9	14.8	1.14	NA	83.2	93.8	0.89	NA	6.16	6.91	0.89	NA
F2-75	16.8	19.6	0.86	NA	118.4	113.7	1.04	A	7.77	6.49	1.20	NA
F3-50	16.1	18.7	0.86	NA	123.2	122.9	1.00	A	8.39	7.18	1.17	NA
Reliability				25%				62.5%				12.5%

*Note: A – Applicable, NA – Not applicable

Table 4: Mechanical properties of specimens based on the predicted and experimental results (Cont.)

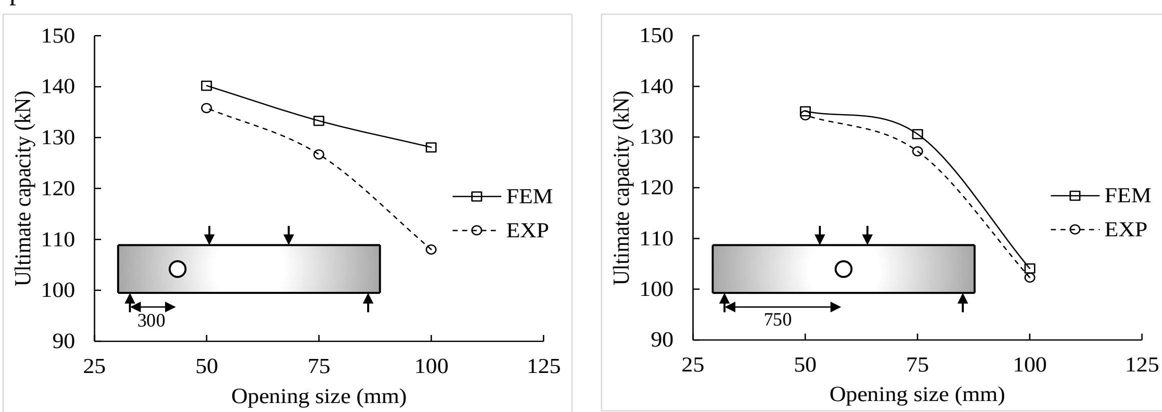
Specimen	Ultimate strength, P_u (kN)				Total deflection, δ_u (mm)				Ductility, Δ*			
	FEM	EXP	R_r	State	FEM	EXP	R_r	State	FEM	EXP	R_r	State
C1-S	185.5	163.11	1.14	NA	10.331	10.2	1.01	A	1.1	1.61	0.68	NA
C2-F	158.6	156.81	1.01	A	9.988	10.42	0.96	A	1.15	1.55	0.74	NA
S1-100	128.1	108.03	1.19	NA	7.349	5.76	1.28	NA	1.2	1.14	1.05	A
S2-75	133.3	126.71	1.05	A	7.748	6.99	1.11	NA	1.23	1.14	1.08	A
S3-50	140.2	135.81	1.03	A	9.609	9.34	1.03	A	1.78	1.43	1.24	NA
F1-100	104.1	102.33	1.02	A	9.027	8.61	1.05	A	1.47	1.25	1.18	NA
F2-75	130.6	127.21	1.03	A	8.855	8.3	1.07	A	1.14	1.28	0.89	NA
F3-50	135.1	134.3	1.01	A	9.716	10.07	0.96	A	1.16	1.40	0.83	NA
Reliability				75%				75%				25%

*Note: The ductility was computed by dividing the total deflection, δ_u, by the deflection at yield, δ_y.

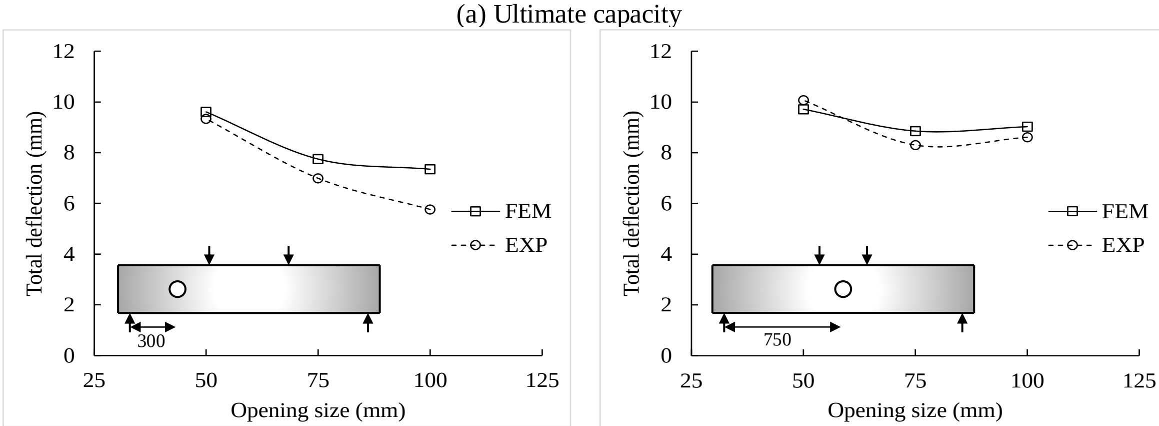
Parametric response

Figure 8 compares the parametric responses of the model and experimental results, particularly the effects of the opening size on the beam performance. In general, the predicted parametric responses for the beam capacity and total deflection, as represented by the trend of the curves, were somewhat similar to the experimental results. It deviated significantly for the other mechanical properties.

In principles, the opening was found affecting the strength and deflection of beam. A larger opening size led to a lower ultimate capacity, yield strength and total deformation of beam. The strength of beam was more significantly affected by the opening size when it was placed at the mid-span. The strength reduction was more drastic than when it is placed near to the support. These findings were in-line with the experimental results. The other responses varied slightly from the experimental results.

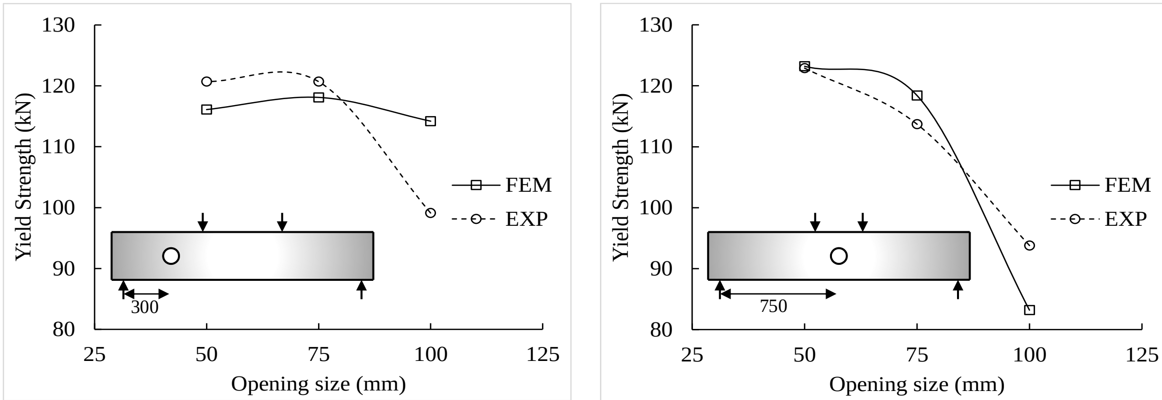


(a) Ultimate capacity

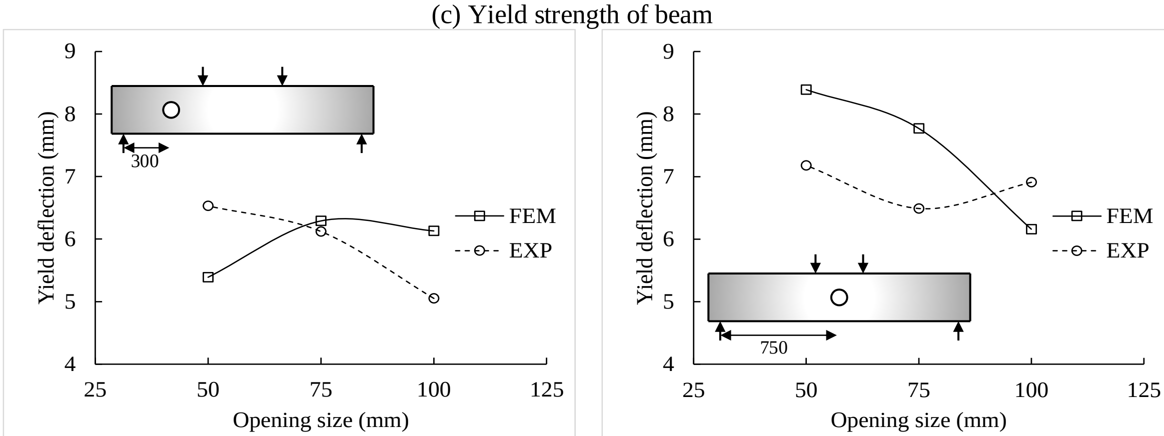


(b) Total deflection of beam

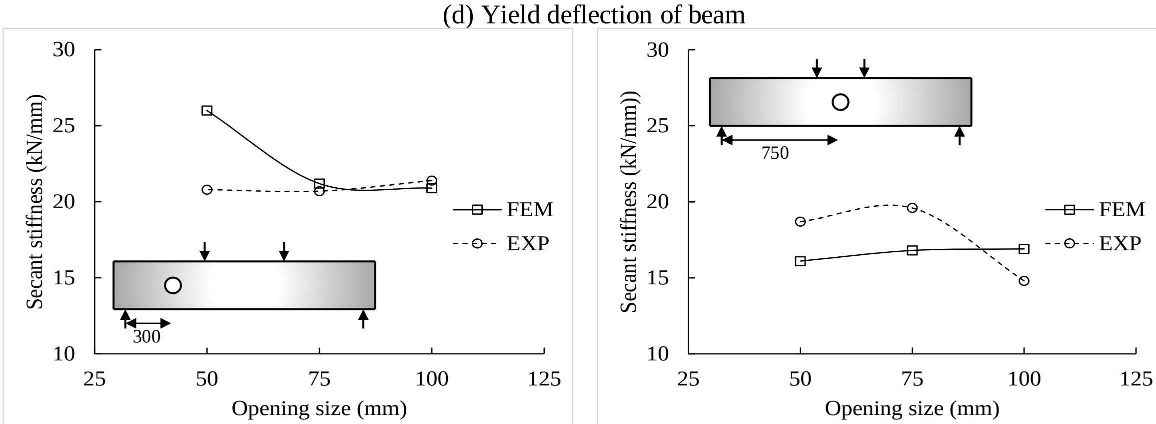
Figure 9: Effects of opening size on beam performance



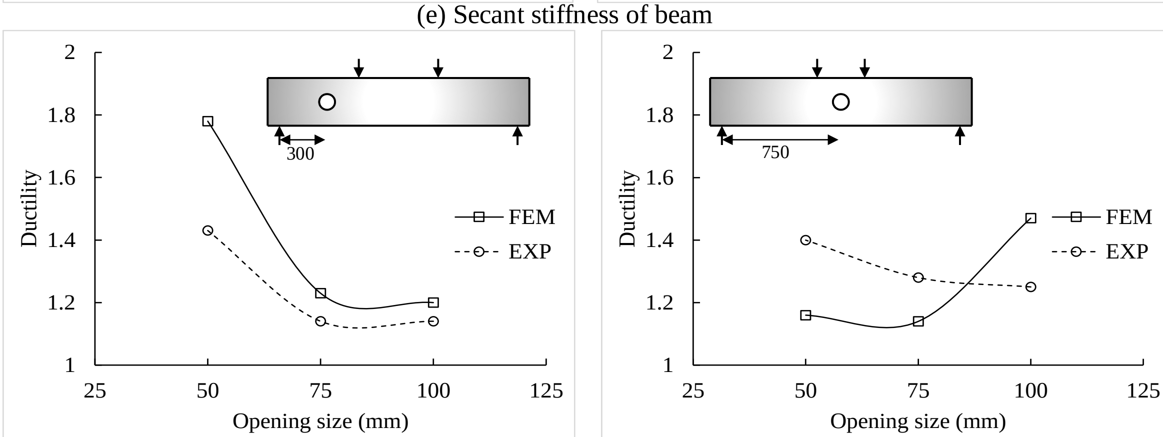
(c) Yield strength of beam



(d) Yield deflection of beam



(e) Secant stiffness of beam



(f) Ductility of beam

Figure 9: Effects of opening size on beam performance (cont.)

CONCLUSION

This paper presents a validation analysis of a FEM model developed to simulate the response of RC beams with a transverse opening. The reliability of the model was evaluated in terms of the load-displacement response, mechanical properties, and the parametric response.

Although the predicted responses of the specimens were somewhat close to the experimental results, the reliability of the model was still questionable. Should the model be used for simulating the actual response of the beam, particularly for further research studies or industrial applications, it should be used with cautions. This includes (a) to strategically cross-check of the predicted results with the actual responses, (b) to apply some factors of safety to maintain an acceptable degree of conservativeness, and (c) to adopt only the results found to have a higher degree of reliability.

Alternatively, one could relook into the model, revise as necessary. This includes fine-tuning (a) the material properties, (b) the boundary conditions, (c) the bonding conditions, (d) meshing size, and etc., as necessary, so that it more closely resembles the actual response of a beam.

ACKNOWLEDGMENT

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