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Punching Shear Capacity of RC Biaxial Voided Slab – Prediction by Critical Shear Crack Theory

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Abstract

In this study the applicability of critical shear crack theory (CSCT) to biaxial voided slab is investigated, which predicts the punching shear capacity of solid slab. Based on the experimental results of biaxial voided slab available in the literature (40 specimens) the research is carried out. The experimental results showed that the load-rotation behaviour of biaxial voided slab is remain same as that of solid slab except for specimens with void located within 0.5*d* from face of the column. Further, the punching shear capacity of slab specimens with voids located beyond 2*d* distance from column face is almost the same as that of the solid slab. Depends on the available load-rotation data modified CSCT was developed depends on the location of the void from face of the column. The predictions were observed to be very scattered with a mean and standard deviation of 0.752 and 0.412, respectively. This is reasonable as the modified CSCT estimates the capacity with respect to the location of voids and ignores the area of void at the section considered. The CSCT approach needs to be further modified by including location and area of void to predict the punching shear capacity of biaxial voided slab with reasonable accuracy.

Keywords: Punching shear, Voided slab, Critical shear crack, Reinforced concrete, Load-rotation

1. Introduction

Biaxial voided reinforced concrete slab is being adopted as an alternative to conventional reinforced concrete (RC) flat slab. It is mainly because of its many advantages over conventional RC slabs, such as reduced self-weight (up to 50%), reduction in consumption of materials in other structural members (about 15%), green technology, reduces carbon emission, and reduction in overall cost [1]. The flexural performance of the biaxial voided slab system is almost remain the same as that of RC solid slab. For example, the one-way ultimate flexural capacity of biaxial voided slab is 84-97% of the solid slab capacity whose dimension and properties are remain the same [2–5]. Similarly, the two-way ultimate flexural capacity of biaxial voided slab is remain the same as that of solid slab. However, the presence of voids affect the initial stiffness marginally [6,7]. As the presence of voids leads to reduction in the effective concrete area, the one-way shear capacity of biaxial voided slab reduces [8]. Similarly, the two-way shear (punching shear) capacity is also significantly affected by the presence of voids [9]. However the punching shear capacity of biaxial voided slab is affected by many parameters such as location of void from the face of column, size of void and void pattern. From the detailed research, it is found that the punching shear capacity of biaxial voided slab is remain the same as that of solid slab, if the void is located beyond 3*d* (*d* is effective depth of slab) distance from the face of column [10]. The prediction of punching shear capacity becomes complicated as the presence of voids alters the critical section. Further, the conventional methodology available for solid slab in the building standards (ACI 318-14, EN 1992-1-1 2004 and IS 456 2000) does not applicale for the void slabs. Hence the Authors [10] introduced an alternate way to predict the punching shear capacity by incorporating suitable modification to the control perimeter and using effective concrete area in the existing equations of various building standards. As the equations available in the building standards and proposed by Authors are semi-empirical in nature, an effective way to predict the punching shear capacity needs to be established.

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1.1 Critical Shear Crack Theory

"*The punching shear strength decreases with increasing rotation of the slab (Figure 1), i.e., the shear strength is reduced by the presence of a critical shear crack that propagates through the slab into the inclined compression strut carrying the shear force to the column*" [11]. The typical correlation between opening of critical shear crack, thickness of slab, and rotation is shown in Figure 2. In continuation with that critical shear crack theory (CSCT) was adopted to develop a failure criterion for punching shear [12,13]. This criterion describes the relationship between the punching shear strength of a solid slab and its rotation at failure (Eq. 1).

$$\frac{V_R}{b_0 d\sqrt{f_c'}} = \frac{3/4}{1+15\dfrac{\psi d}{d_{g0}+d_g}} \tag{1}$$

where, V_R is punching shear strength, f_c' is characteristic compressive cylinder strength of concrete, b_0 is perimeter of critical section (which is located at a distance of 0.5d from face of the column) for two-way shear in slabs, d is effective depth of slab, ψ is rotation, d_{g0} is reference aggregate size (= 16 mm), and d_g is maximum aggregate size.

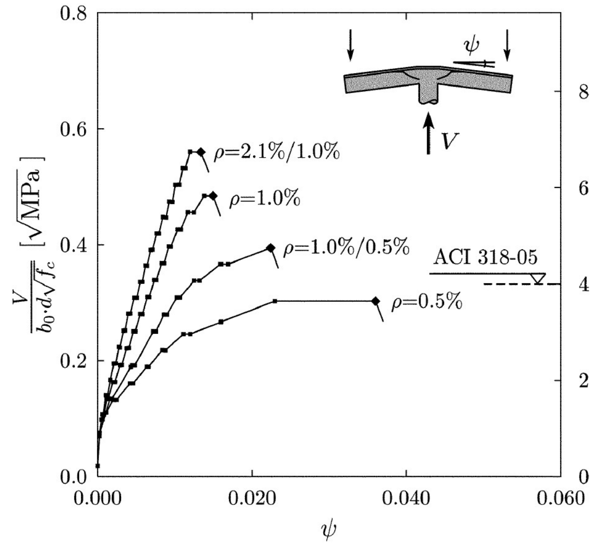

Fig. 1 – Load-rotation curves for tests by Kinnunen and Nylander [13]

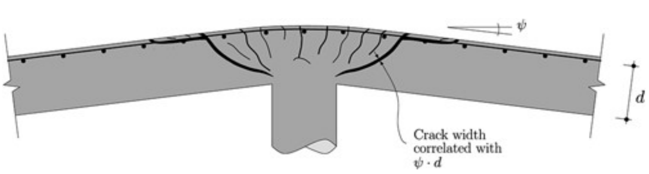

Fig. 2 – Correlation between opening of critical shear crack, thickness of slab, and rotation [13]

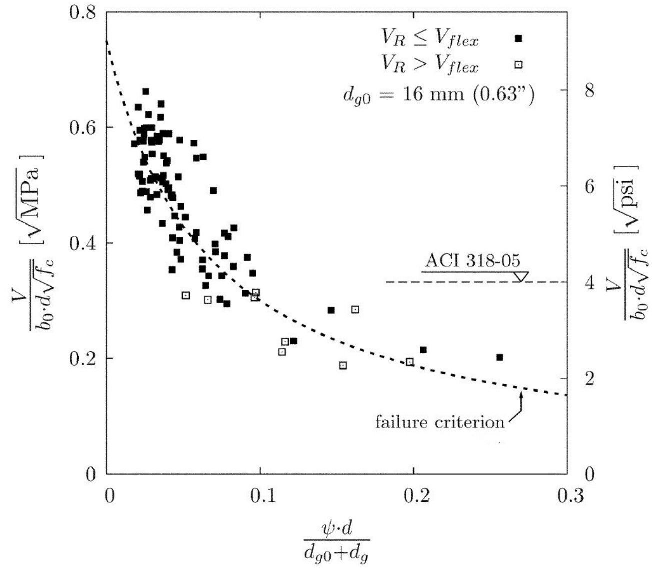

Fig. 3 – Failure Criterion [13]

The failure criterion (Eq. 1) was developed by Muttoni [13] based on the 99 experimental results as shown in Figure 3. For more details regarding the experiments that were considered for the same can be obtained in the article by Muttoni [13].

2. Load – Rotation Relationship of Biaxial Voided Slab

The punching shear strength of solid slab is depends on its rotation, i.e., the strength decreases with increasing rotation. Hence, it is very important to understand the variation in the load-rotation relationship of biaxial voided slab in comparison with that of solid slab. The rotation is directly depends on the deflection of the slab. So the load-rotation relationship remains the same as that of load-deflection of the slab. In order to verify the load-deflection relation of solid and biaxial voided slabs, the experimental results available in literature [10,14] are considered. For more details regarding the experiments that were considered for the same can be obtained in the relevant articles. From the experimental results (Figure 4), it is observed that the load-deflection behaviour of biaxial voided slab remains the same as that of solid slab irrespective of the void shape. However, if the location of the void from face of the column lies within 0.5d, then the load-deflection behaviour gets affected marginally (specimen V2 in Figure 4b). As a summary, the relationship between the punching shear strength of a solid slab and its rotation at failure (Eq. 1) remains applicable for biaxial voided slab with necessary modification to account for reduction in punching shear strength depends on the location of void from the face of column.

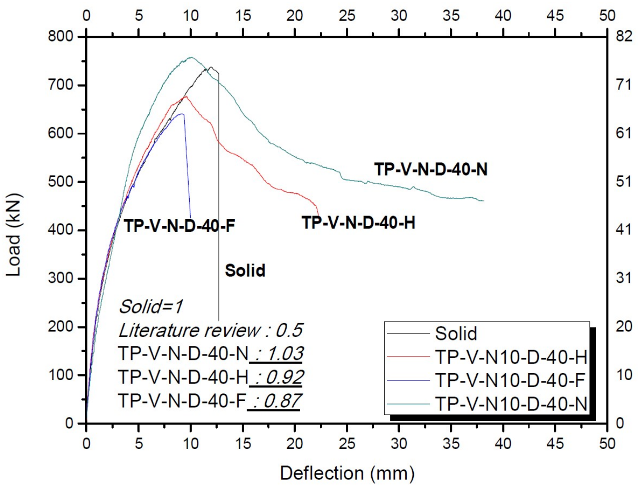

Fig. 4(a) – Load versus deflection relation of tested specimens [14]

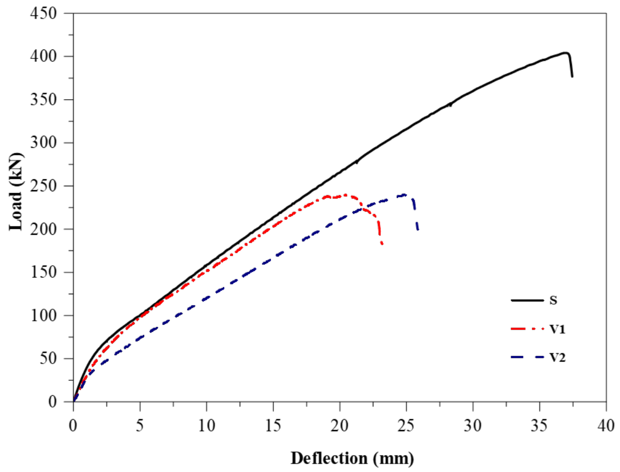

Fig. 4(b) – Load versus deflection relation of tested specimens [10]

3. Prediction of Punching Shear Capacity

The applicability of the CSCT (Eq. 1) for the biaxial voided slab is verified in this section. In this study, the experimental results available in the literature (40 specimens) were compared with the estimations. The details and experimental results of voided slab specimens are summarised in Table 1. The CSCT approach requires the ultimate load (punching shear) and corresponding deflection. Hence, the specimens (29 specimens) with both punching shear load and corresponding deflection are considered for initial observations.

Figure 5 shows the data points of the normalised load and rotation of 29 test specimens. The punching shear capacity of slab specimens with voids located beyond 2*d* distance from column face is almost the same as that of the solid slab (Figure 5). However, if the void is located beyond *d* (and within 2*d*) distance from the column face, then the punching shear capacity is reduced about 30%. Similarly, for slab specimens with voids located close to column face (<*d*), the punching shear capacity is reduced about 60%. Hence capacity reduction factor (α) is introduced in the Eq. 1 as given in Eq. 2 depends on the location of void from the face of the column.

$$\frac{\alpha V_R}{b_0 d\sqrt{f_c'}} = \frac{3/4}{1+15\dfrac{\psi d}{d_{g0}+d_g}} \tag{2}$$

where,

$$\alpha = \begin{cases} 1.0 & \text{void location} > 2d \\ 0.6 & d < \text{void location} < 2d \\ 0.3 & \text{void location} < d \end{cases} \tag{3}$$

Based on this understanding, the modified CSCT (Eq. 2) is applied to all 40 test specimens and found that the predictions were observed to be very scattered with a mean and standard deviation of 0.752 and 0.412, respectively (Figure 6). In particular the calculated capacity for the specimens with void located very close to column face (<0.5*d*) is observed to be

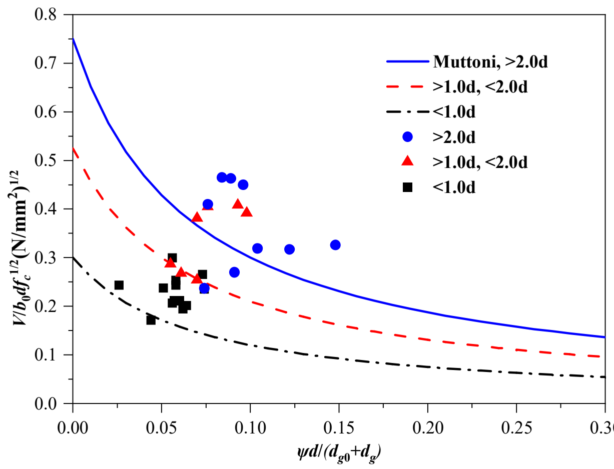

Fig. 5 – Failure Criterion: Punching Shear Strength as Function of Width of Critical Shear Crack

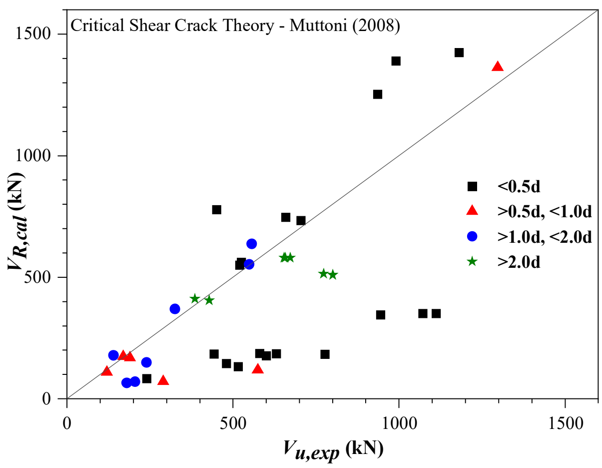

Fig. 6 – Comparison of punching shear capacity of voided slab specimens (Table 1) and CSCT

Table 1 – Details and Experimental Results of Voided Slab Specimens of Various Researchers

Reference	ID	Void location from column face	Effective depth, d (mm)	Square column size, a (mm)	Concrete strength, f_c' (N/mm^2)	Max. aggregate size, d_g (mm)	Radius r_q (mm)	Failure load V_u (kN)	Deflection δ (mm)
Held and Pfeffer [15]	D1-24	0.31d	190.0	300	35.52	16	1125	520	–
	D2-24	0.31d	190.0	300	40.64	16	1125	557.6	4.96
	D3-24	0.31d	190.0	300	37.36	16	1125	525	–
	D4-45	0.18d	380.0	300	23.68	16	1125	935	–
	D5-45	0.18d	380.0	300	30.32	16	1125	990	–
	D6-45	0.18d	380.0	300	32.40	16	1125	1180	–
Han and Lee [16]	V1	0.66d	373.5	267	33.00	16	900	1297	6.27
	V2	0.34d	373.5	267	33.00	16	900	1071	5.20
	V3	0.34d	373.5	267	33.00	16	900	1111	5.38
	V4	0.34d	373.5	267	33.00	16	900	944	3.68
Oukaili and Husain [17]	BD1	2.00d	77.0	100	30.50	16	700	140	24.50
	BD3	2.00d	105.0	100	28.00	16	700	205	20.45
	BD5	1.00d	77.0	100	29.50	16	700	120	22.10
	BD7	1.00d	105.0	100	31.70	16	700	190	20.90
	BD9	2.00d	77.0	100	65.00	16	700	180	22.10
	BD11	2.00d	105.0	100	66.50	16	700	325	18.88
	BD13	1.00d	77.0	100	67.00	16	700	170	20.22
	BD15	1.00d	105.0	100	68.00	16	700	290	19.75
Valivonis et al. [18]	BPR1-1	0.34d	234.6	350	26.51	12	1505	600.2	12.27
	BPR1-2	0.34d	234.8	350	26.51	12	1505	600.1	11.61
	BPR2-1	0.34d	232.9	350	28.95	12	1505	776.3	15.13
	BPR2-2	0.34d	235.0	350	28.95	12	1505	704.5	10.40
	BPR3-1	3.33d	152.9	350	27.96	12	1505	385.4	23.28
	BPR3-2	3.40d	150.0	350	27.96	12	1505	428.1	29.13
Valivonis et al.[19]	BP1-1	2.18d	233.9	350	31.01	12	1505	772.7	–
	BP1-2	2.19d	232.5	350	31.01	12	1505	800.5	–
	BP2-1	0.35d	225.7	350	32.07	12	1505	443.1	–
	BP2-2	0.34d	236.3	350	32.07	12	1505	450.9	–
	BP3-1	0.35d	231.1	350	30.38	12	1505	630.4	–
	BP3-2	0.34d	234.0	350	30.38	12	1505	658.4	–
Chung et al. [20]	PD-N-0	1.31d	217.0	300	21.40	16	1275	758.1	9.98
	PD-N-4	0.07d	217.0	300	22.20	16	1275	677.1	9.53
	PD-N-8	0.07d	217.0	300	26.80	16	1275	641.5	9.20
Sagadevan and Rao [10]	V1	1.05d	119.0	300	22.48	12	1500	239.8	20.51
	V2	0.38d	119.0	300	22.48	12	1500	240.4	24.83
	V3	0.51d	205.0	300	21.36	12	1500	574.4	11.52
	V4	1.07d	205.0	300	21.36	12	1500	548.9	11.37
	V5	2.26d	221.0	300	20.00	12	1500	657.2	19.70
	V6	2.26d	221.0	300	20.00	12	1500	672.3	28.12
	V7	2.26d	221.0	300	20.00	12	1500	653.6	23.13

Note: # Concrete cylinder strength is taken as 80 % of cube strength and vice versa, if required lesser than that of experimental results. This is reasonable as the modified CSCT estimates the capacity with respect to the location of voids and ignores the area of void at the section considered.

4. Summary and Conclusions

The applicability of critical shear crack theory which predicts the punching shear capacity of solid slab to biaxial voided slab is investigated in this study. For the purpose of the same, the experimental results available in the literature (40 specimens) were collected. Based on the available load-rotation data modified CSCT was developed depends on the location of the void from face of the column. The experimental results showed that the load-rotation behaviour of biaxial voided slab is remain same as that of solid slab except for specimens with void located within 0.5*d* from face of the column. Further, the punching shear capacity of slab specimens with voids located beyond 2*d* distance from column face is almost the same as that of the solid slab. The predictions by modified CSCT were observed to be very scattered with a mean and standard deviation of 0.752 and 0.412, respectively. This is reasonable as the modified CSCT estimates the capacity with respect to the location of voids and ignores the area of void at the section considered. The CSCT approach needs to be modified by including location and area of void, which needs more experimental results. Further, the study needs to be extended to investigate the crack propagation through the voids, as the presence of voids affects the critical section of punching shear.

Disclosures

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