Comparative analysis of punching shear strength for reinforced concrete slabs based on database

Chuanteng Huang[a], Qing Ma and Shuang Pu

School of Engineering and Technology, Zunyi Normal College,Zunyi, Guizhou, P. R. China

Abstract. Although various studies and hundreds of laboratory experiments related to the punching shear strength of reinforced concrete (RC) slabs have been published and conducted respectively, code provisions have been developed based on a rather limited subset of the available test results and those studies ignored the details of test slabs and experiments. A database of 678 specimens has been categorized and structured depending on the test set-up type through the present study. In this study, eight equations for the punching shear strength prescribed in specifications were evaluated based on the database. A simplified strength equation is also proposed from the database.

Keywords: code provisions, flat slabs, punching shear, structural design.

1 Introduction

In the late 1940's, flat plates were initially developed in the U.S. Since then, hundreds of laboratory experiments have been conducted to investigate the punching shear behavior of two-way reinforced concrete (RC) slabs at interior supports. In general, most researches distinguished the controlling factors of punching shear strength based on regression analysis of experimental data and elastic theory, and formulated all the controlling factors empirically to calculate the punching shear strength.

Unfortunately, because of arbitrariness by researchers and code developers in selecting reference data together with ignored the details of test slabs and experiments, code provisions have been developed based on a rather limited subset of the available test results and also based on the not detailed categorized tests. Until now, almost all structural design codes judge punching shear failure by the nominal stress in the critical section. However, there are divergences in aspects of location of the critical section, shape of the critical section, calculation method of the nominal stress, value of the ultimate stress and othercontrolling factors[1,2], shown as Figure 1 and Table 1.

Ospina et al.[1]reported the basis of the punching databank containing 512 test results of slabs without shear reinforcement subjected to concentric punching at interior column locations. However, Ospina missed Chinese and Japanese paper written in Chinese and Japanese, respectively.

The purposes of the present study are to create database for the punching shear strength of RC slabs, to evaluate the equations proposed in specifications, and to propose a rational strength equation. The member strength factors based on the evaluated equation and failure probability are also determined in this study.

[a] Corresponding author : huangct@yeah.net

Table 1. Specifications of different Codes for punching shear strengtha.

Design code	Critical section (u)	Effective height (d)[c]	Concrete strength[c]	Size effect(S_e)	Other factors (η)[d]	Punching shear strength (V)	Inclination of critical section (θ)
GB (2010)[1]	Fig. 1(a)(b)	$(d_x+d_y)/2$	f_t	1.0-(d-800)/12000; $0.9\leq S_e\leq 1.0$	$\eta_1=f_1(c_1/c_2)$; $\eta_2=f_2(d/u)$ $\eta=\min(\eta_1,\eta_2)$	$0.7S_e f_t\eta ud$	63.4
ACI (2011)[2]	Fig. 1(a)(b)	$(d_x+d_y)/2$	$f_c'^{1/2}$	-	$\eta_1=f_3(c_1/c_2)$; $\eta_2=f_4(d/u)$ $\eta=\min(\eta_1,\eta_2,0.33)$	$f_c'^{1/2}\eta ud$	63.4
CEB-FIP (2010)[3]	Fig. 1(a)(c)	$(d_x+d_y)/2$	$f_{ck}^{1/2}$	-	$\eta=f_5(E_s,f_y,d_g,r_s)$	$f_{ck}^{1/2}\eta ud$	63.4
BS (1997)[4]b	Fig. 1(d)(e)	$(d_x+d_y)/2$	$f_{cu}^{1/3}$	$(400/d)^{1/4}$; $S_e\geq 1.0$	$\eta=f_6(\rho)$; $\rho\leq 0.03$	$0.79S_e(f_{cu}/25)^{1/3}\eta ud$ *2	33.7
CAN (2010)[5]	Fig. 1(a)(b)	$(d_x+d_y)/2$	$f_c'^{1/2}$	1300/(1000+d); $d\geq 300$	$\eta_1=f_7(c_1/c_2)$; $\eta_2=f_8(d/u)$ $\eta=\min(\eta_1,\eta_2,0.38)$	$S_e f_c'^{1/2}\eta ud$	63.4
EN (2004)[6]	Fig. 1(g)(h)	$(d_x+d_y)/2$	$f_{ck}^{1/3}$	$1+(200/d)^{1/2}$; $S_e\leq 2.0$	$\eta=f_6(\rho)$; $\rho\leq 0.02$	$0.18S_e f_{ck}^{1/3}\eta ud$	26.6
DIN (2008)[7]	Fig. 1(d)(f)	$(d_x+d_y)/2$	$f_{ck}^{1/3}$	$1+(200/d)^{1/2}$; $S_e\leq 2.0$	$\eta=f_6(\rho)$; $\rho\leq 0.02$	$0.21S_e f_{ck}^{1/3}\eta ud$	33.7
JSCE (2002)[8]	Fig. 1(a)(b)	$(d_x+d_y)/2$	$f_c'^{1/2}$	$(1000/d)^{1/4}$; $S_e\leq 1.5$	$\eta_1=f_6(\rho)$; $\eta_2=f_9(c_1,c_2,d)$ $\eta_1\leq 1.5$, $\eta=\eta_1\times\eta_2$	$0.2S_e f_c'^{1/2}\eta ud$	63.4

Note:

[a] Units in Table 1 are MPa and mm;

[b] When f_{cu}<25MPa, f_{cu} =25; and $f_{cu}\leqslant$40MPa;

[c] d_x and d_y are the effective height in two orthogonal directions; f_t, f_c', f_{ck}, f_{cu} are the axial tension strength, cylinder compressive strength, eigenvalue of compressive strength, cubic (150mm×150mm×150mm) compressive strength of concrete, respectively;

[d] c_1 and c_2 are the long side and short side of rectangular column, respectively, when c_1/c_2<2, c_1/c_2=2, and c_1/c_2=2 for the round column; the functions in Table 1: f_1: 0.4+1.2/(c_1/c_2); f_2: 0.5+0.25$\alpha_s d/u$; f_3: 0.166+0.332/(c_1/c_2); f_4: 0.166+0.083$\alpha_s d/u$; f_5: 1/[1.5+43.2$r_s f_y$/(16+d_g)/E_s]; f_6: (100ρ)1/3; f_7: 0.19+0.38/(c_1/c_2); f_8: 0.19+0.1$\alpha_s d/u$; f_9: 1+1/[1+0.5(c_1+c_2)/d]; where α_s is 40 for interior columns, 30 for edge columns, 20 for corner columns; ρ is the reinforcement ratio; r_s denotes the position where the radial bending moment is zero with respect to the support axis; d_g is the maximum size of the aggregate; E_s is the elastic modulus of steel.

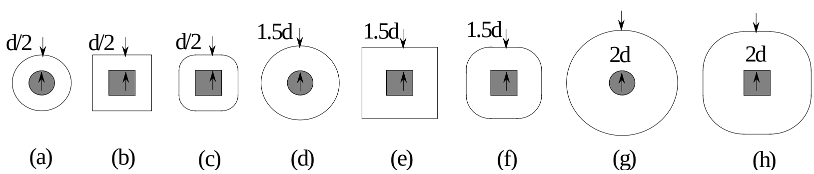

Figure 1. Position and perimeter of the critical section.

2 Database and evaluation of design specifications

2.1. Database and categorization

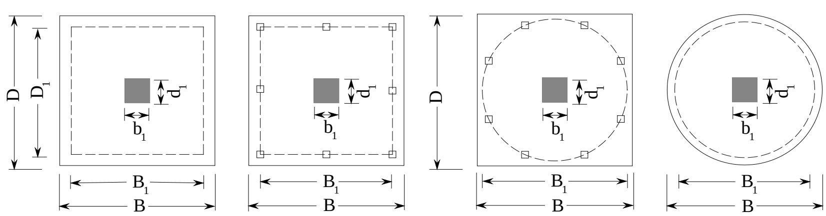

Figure 2. Test specimen descriptors.

Table 2. Classification of test specimen.

Group	Slab Supported or loadedPattern - Column shape	Number of specimen	Filter out	Surplus specimen
CC	Circular - Circular	136	22	114
CS	Circular - Square	67	10	57
R(RCS)	Rectangular - (Rectangular,Circular, Square)	4+5+7	0	16
SC	Square - Circular	30	2	28
(SC)R	(Square, Circular) - Rectangular	21+2	0	23
SS	Square - Square	324	6	318
O	Opposite -	35	0	35
U	Slab Uniformly Loaded-	47	0	47
Total		678	40	638

The specifications of eight different codes for punching shear strength are given in Table 1. The author[1] collected 166 test results of slabs without shear reinforcement subjected to concentric punching at interior column locations which conducted in China and Japan. Together with Ospina, the database of 678 specimens has been created. Shown as in Table 2, the 678 specimens were categorized in 8 main types according to the test set-up and the specimen geometry. Figure 2 shows the plan view of typical test specimens indicating the different variables and notation used to describe their geometric properties in plan and support conditions. It should be note that the tests which missing key data will be removed.

Table 3. Comparison among calculation results by different Codes.

Group	Index [a]	GB	ACI	CEB /FIP	BS	CAN	EN	DIN	JSCE	Total
CC	AVG	1.491	1.676	1.911	1.244	1.456	1.24	1.28	1.119	1.427
	ST	0.509	0.556	0.724	0.303	0.482	0.328	0.328	0.302	0.524
	COV	0.341	0.332	0.379	0.244	0.331	0.264	0.256	0.269	0.367
CS	AVG	1.031	1.163	1.646	0.952	1.011	1.036	1.059	0.926	1.103
	ST	0.321	0.346	0.51	0.155	0.299	0.213	0.21	0.231	0.371
	COV	0.311	0.298	0.31	0.162	0.296	0.206	0.198	0.249	0.336
R(RCS)	AVG	1.351	1.503	2.501	1.058	1.32	1.116	1.159	1.066	1.384
	ST	0.333	0.342	1.089	0.203	0.274	0.114	0.131	0.186	0.624
	COV	0.246	0.228	0.435	0.192	0.207	0.102	0.113	0.174	0.451
SC	AVG	1.401	1.566	1.799	1.314	1.36	1.225	1.28	1.227	1.396
	ST	0.304	0.319	0.344	0.133	0.277	0.135	0.148	0.252	0.309
	COV	0.217	0.204	0.191	0.101	0.204	0.11	0.116	0.205	0.222
(SC)R	AVG	1.26	1.366	1.464	1.064	1.191	1.148	1.149	1.011	1.207
	ST	0.287	0.288	0.366	0.167	0.252	0.146	0.14	0.144	0.273
	COV	0.228	0.211	0.25	0.157	0.211	0.127	0.122	0.142	0.226
SS	AVG	1.285	1.455	1.718	1.115	1.265	1.289	1.309	1.117	1.319
	ST	0.423	0.479	0.861	0.352	0.415	0.414	0.414	0.352	0.521
	COV	0.33	0.329	0.501	0.316	0.328	0.321	0.316	0.315	0.395
O	AVG	0.935	1.056	1.544	0.864	0.918	0.868	0.899	0.802	0.986
	ST	0.245	0.281	1.005	0.195	0.244	0.226	0.235	0.226	0.47
	COV	0.262	0.266	0.651	0.226	0.266	0.261	0.262	0.282	0.477
U	AVG	1.437	1.621	2.504	1.312	1.404	1.624	1.607	1.286	1.599
	ST	0.381	0.438	0.728	0.287	0.381	0.337	0.342	0.221	0.55
	COV	0.265	0.27	0.291	0.219	0.271	0.208	0.213	0.172	0.344
Total	AVG	1.297	1.462	1.809	1.13	1.27	1.247	1.27	1.095	1.322
	ST	0.436	0.485	0.823	0.322	0.42	0.381	0.378	0.323	0.516
	COV	0.336	0.332	0.455	0.285	0.331	0.305	0.298	0.295	0.39

Note:

[a] AVG, ST, COV are the Statistical Index (average value, standard deviation and coefficient of variation, respectively) for the ratio of test punching result to calculation result by the specifications.

2.2 Evaluation of design specifications

Table 3 provides the statistical index (AVG, ST,COV) of V_{test}/V_{Codes}. From the different Codes results in each group, due to limited test data, the strength equations and computational accuracyvary widely. The strength equations provided in specifications are mostly based on specific test data which contained a small scale in specimen geometry and material parameter. From the results of each specifications among 8 groups, it is obvious that the test set-up and the specimen geometry can influence the computational accuracy significantly. That is to say, the arbitrariness of researchers and code developers in selecting reference data can lead topoorer applicability of the specifications.

3 Proposed rational equation for punching shear strength

To study the punching behaviors of slab-column connection, based on the experimental phenomena, a relatively comprehensive bending-shearing critical crack model (BSCCM) which can be used to calculate the punching load and deformation simultaneously was established by the author[12].

The BSCCM[12]indicated that the factors that affect punching behavior include: reinforcement ratio (ρ), concrete strength (f_c), yield strength of steel (f_y), punching span ratio (λ) and perimeter thickness ratio of critical section (b_0/d). Reinforcement ratio and yield strength of steel are negatively correlated with punching deformation and positively correlated with punching capacity. In contrast, concrete strength, punching span ratio and perimeter thickness ratio of critical section are positively correlated with punching deformation and negatively correlated with punching capacity. Therefore, this paper constructs the comprehensive parameter K_0 here (as shown in Eq.1) which represents the comprehensive influence of above factors on punching capacity and punching deformation.

$$K_0 = \frac{\rho f_y}{\sqrt{f_c}\lambda b_0 / d} \tag{1}$$

By numerous theory calculation and parameter analysis, the simple formulas were deduced to calculate the punching load and deformation:

$$\psi\lambda d = 6.613 + 46.469 \cdot e^{-K_0/0.00603} \tag{2}$$

$$100 \cdot v_0 = 15.498 + 62.780 \cdot e^{-\psi\lambda d/16.913} \tag{3}$$

$$v_0 = \frac{V}{\sqrt{f_c} b_0 d} \tag{4}$$

Where ψ is the punching rotation; λ is the punching span ratio; d is the effective thickens of the section;$\psi\cdot\lambda\cdot d$ represents the deflection deformation when punching occurs on the component. V is the punching load; $f_c^{1/2}$ is the concrete item, referring to the standards of different countries to select 1/2 time of concrete strength for consideration; b_0 is the perimeter of the critical section (calculating according to the fillet section which is 0.5d far from the column edge); d is the effective thickness of the slab; $V/(f_c^{1/2}\cdot b_0\cdot d)$ represents the regular nominal punching capacity.

The paper selects two group of tests, CC and SS, to make the detailed discussion. There are two reasons for extracting those two test data: first of all, the component shape and the loading mode are the most regular and the closest to the theoretical method built previously; secondly, most researchers have chosen those two ways for test, being 136 and 324, respectively, accounting for 67.85% of the total test components collected, so the analysis results of those two groups of components are the most representative.

Table 4. Calculation results of punching shear strength.

Calculate method	CCGroup		SSGroup	
	AVG	COV	AVG	COV
Eq. (1)~(4)	1.00	0.188	1.075	0.173
GB50010-2010	1.491	0.341	1.285	0.330
ACI318-11	1.676	0.332	1.455	0.329
CEB/FIP MC2010	1.911	0.379	1.718	0.501
BS 8110-97	1.244	0.244	1.115	0.316
CAN/CSA A23.3-04 (R2010)	1.456	0.331	1.265	0.328
EN 1992-1-4: 2004	1.240	0.264	1.289	0.321
DIN 1045-1: 2008	1.280	0.256	1.309	0.316
JSCE2002	1.119	0.269	1.117	0.315

4 Conclusion

The calculation results are shown inTable 4. The statistical results in the table are the ratios of the test values to the calculated values of punching strength. It can be seen that the calculated method suggested in the paper (Equation 1~4) has the best results. The calculation results of the rest 8 design codes have great deviations, in which JSCE code has the best calculation results. The method suggested in the paper considers the influence of size effect, concrete strength, reinforcement ratio and perimeter thickness ratio of critical section on punching strength and further considers the influence of punching span ratio.

Acknowledgments

This study was funded by research grant from the Doctoral Program Foundation of Zunyi Normal College (BS[2015]17[#]) and Science and Technology Department of Guizhou Province (LH[2016]7005),which are gratefully acknowledged.

References

1. *GB50010-2010 Code for seismic design of buildings*. Beijing: China Architecture & Building Press,2010.(in Chinese).
2. *ACI 318-11 Building Code Requirements for Structural Concrete and Commentary*. Detroit, FarmingtonHills: American Concrete Institute, 2011.
3. *CEB-FIP Mode Code for Concrete Structures 2010*. Wilhelm Ernst &Sohn, Berlin, Germany, 2010.
4. *BS 8110-97 Structural use of concrete, Part 1: Code of Practice for Design and Construction*. British Standards Institution, London, UK, 1997.
5. *CAN/CSA-A23.3-04 (R2010) - Design of Concrete Structures*. Canadian Standards Association, Rexdale, ON, Canada, 2010.
6. *BS EN 1992-1-1:2004 Design of Concrete Structures. General rules and rules for buildings*. Brussels, Belgium, 2004.
7. *DIN 1045-1: 2008 Plain, Reinforced and Prestressed Concrete Structures-Part 1: Design and Construction*. NormenausschussBauwesen (NABau) im DIN DeutschesInstitutfürNormunge.V. BeuthVerl. Berlin, 2008.
8. *Standard specification for concrete structures-2002*. Japan Society of Civil Engineering.
9. Hamada S, Yang Q, Mao M. Journal of Advanced Concrete Technology, 2008, 6(1): 205-214.
10. Gardner N J. ACI Structural Journal, 2011, 108(5): 572-580.
11. Carlos E. Ospina, GerdBirkle, WidiantoWidianto (2011). *ACI 445 Punching Shear Collected Databank*, Network for Earthquake Engineering Simulation (database), Dataset, DOI: 10. 4231/D3TX35618.
12. Huang C T. *Study on the Analysis Methods of Hollow Floor and Punching Issues of Slab-column Connection*,PhD thesis, School of Civil Engineering, Chongqing University, Chongqing, China (2015).(in Chinese).

