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Study on punching shear strength of reinforced concrete slabs subjected to rapid loading

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ABSTRACT : In most of the evaluations of the punching shear strength of reinforced concrete slabs and walls which are subjected to rapid loading caused by soft missile impact such as aircraft crash, experimental equations have been applied.

We investigated the past representative equations for punching shear strength from the view point of the applicability for thick slabs which are subjected to extreme loading. Furthermore, considering the effects of the shear reinforcements and the strain rate effects under rapid loading, the evaluation method of punching shear strength was proposed.

The applicability of the proposed evaluation method was verified comparing the calculated values with the past experimental results of the static and dynamic loading tests, and the good agreement was obtained.

1. INTRODUCTION

In most of the evaluations of the punching shear strength of reinforced concrete slabs and walls which are subjected to rapid loading caused by soft missile impact such as aircraft crash, experimental equations have been applied. Most of past calculating equations for punching shear failure were suggested to express the punching shear strength of slab at column tops of flat slab having thin and medium-thickness, and the applicability for thick slabs subjected to extreme loadings such as aircraft crash has not been well verified. Further, the effects of shear reinforcement and the strain rate effects of materials under rapid loading have not been well verified. In relation to risk analysis on the protective design against aircraft crash, it is desired to establish a rational evaluation method of punching shear strength considering these effects.

We discuss the punching shear strength calculation method of reinforced concrete plates which are subjected to rapid loading focusing to the above mentioned effects.

2. INVESTIGATION OF THE PUNCHING SHEAR CAPACITY CALCULATING EQUATIONS

2.1 Shear strength of the plates without shear reinforcement

The equations by ACI[1)], by Kakuta et. al[2)] and by Japan Society of Civil Engineers

(JSCE)[3] are selected as representative static punching shear strength calculating equations considering that these expressions agree well with the experimental data[2].

The slab thickness(1.0~2.0m) in the protective design against large commercial airplane or fast flying military airplane is considerably larger than that of the experiment (0.1~0.2m). Therefore scale effect must be taken into account in the strength evaluation. The shear strength for thicker plates normalized by the strength of the plate with 10cm effective thickness is shown in Fig.1.

The differences of the strength by the equations become large with increasing thickness, and it is apparent that the ACI equation has no scale effect.

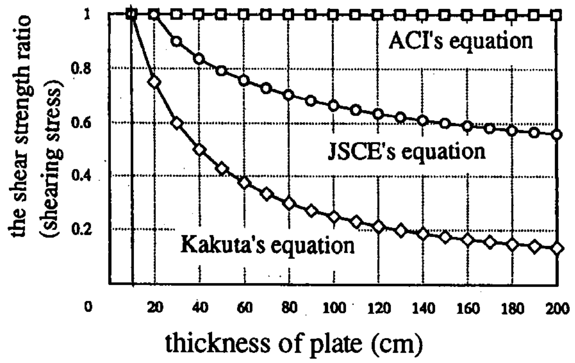

Fig.1 Comparison of scale effect in each equation

The scale effect taken into account in the JSCE equation was assured by the experiments covering the range of thick slabs. Therefore we judged that JSCE equation (1) was most appropriate among these equations for application.

The JSCE equation is shown below.

$$V_u = f_{pcd} \cdot u_p d / \gamma_b \qquad (1)$$

where

$$f_{pcd} = 0.6 \cdot \beta_d \cdot \beta_p \cdot \beta_r \sqrt{f'_{cd}} \quad (\mathrm{kgf/cm^2})$$

$$\beta_d = \sqrt[4]{100/d} \leqq 1.5$$

$$\beta_p = \sqrt[3]{100p} \leqq 1.5$$

$$\beta_r = 1 + 1/(1+0.25u/d)$$

V_u : ultimate shear strength (kgf)
f'_{cd} : compressive strength of concrete (kgf/cm^2)
u : perimeter of loaded area (cm)
u_p : perimeter of critical section located d/2 from loaded area for plate (cm)
d : effective depth (cm)
p : reinforcement ratio
γ_b : design factor (set to be 1.0 in the present case)

2.2 Effect of the shear reinforcement

The ultimate shear strength of the plates with shear reinforcement can be predicted by combination of the ultimate strength of the shear reinforcement and the ultimate strength of the plate without shear reinforcement calculated by the JSCE equation.

According to the method in the ACI code[1], the sum of half the strength without shear reinforcement (Vu) and the ultimate strength of the shear reinforcement (Vs) is compared with the strength of a plate without shear reinforcement, and the greater value is considered to be the ultimate strength.

The ultimate strength of the shear reinforcement is given by Eq.2 assuming inclined cracking 45° from compressive edge.

$$Vs = pw \cdot \sigma y \cdot Up \cdot d \qquad (2)$$

pw : shear reinforcement ratio
σy : yield strength of the shear reinforcement

Upper limit of the shear stress is considered to be $3.5\sqrt{fc'd}$ referring to the results in the Ref. 4.

2.3 Dynamic increasing factor of the material strength

As is generally known, the material strengths increase with increasing strain rate for rapid loading.

In our study, the following increasing factors of tensile strength of concrete and yield strength of reinforcement are taken into account. The factors were suggested by Yamaguchi et. al[5].

· Tensile strength of concrete

for $\dot{\gamma}_{oct} > 24.4 \times 10^{-6}$/sec
$F_{td}/F_t = u_1 + u_2 \cdot \log(\dot{\gamma}_{oct}) + u_3 \cdot [\log(\dot{\gamma}_{oct})]^2$
for $\dot{\gamma}_{oct} \leqq 24.4 \times 10^{-6}$/sec
$F_{td}/F_t = 1$

where
F_{td} is tensile strength of concrete for rapid loading
F_t is uni-axial tensile strength for static loading
$u_1=0.8267,\ u_2=0.2987 \times 10^{-1},\ u_3=0.4379 \times 10^{-1}$
$\dot{\gamma}_{oct}$ is the octahedral normal strain rate.

The relationship between octahedral normal strain rate and normal strain rate($\dot{\varepsilon}_1$) is expressed as follows.
$\dot{\gamma}_{oct} = 2\sqrt{2}/3 \cdot (1+\nu) \cdot \dot{\varepsilon}_1$
where ν is Poisson's ratio

· Yield strength of reinforcement

for $\dot{\varepsilon}_1 \geqq 22.5 \times 10^{-6}$/sec
$\sigma_{yd}/\sigma_{ys} = y_1 + y_2 \cdot \log(\dot{\varepsilon}_1) + y_3 \cdot [\log(\dot{\varepsilon}_1)]^2$
$y_1=0.9905,\ y_2=0.1153 \times 10^{-2},\ y_3=0.6725 \times 10^{-2}$
for $\dot{\varepsilon}_1 < 22.5 \times 10^{-6}$/sec
$\sigma_{yd}/\sigma_{ys} = 1$

where
σ_{yd} is yeild strength of reinforcement for rapid loading
σ_{ys} is yeild strength for static loading

The relations between the uni-axial strain rate and the increasing factor of the strength calculated by above mentioned equation are shown in Fig.2.

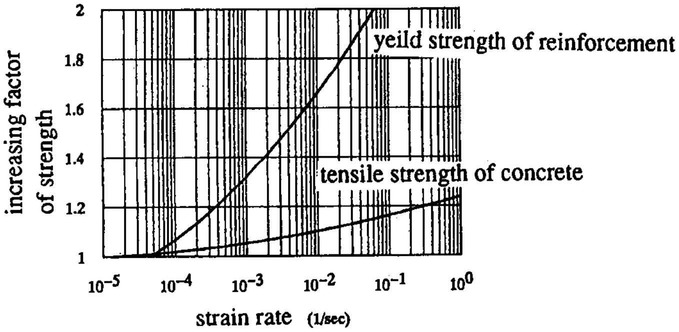

Fig.2 Dynamic increasing factor of the material strength

The strength increase is taken into account in the calculation of ultimate shear strengths of the plates by following manner.

First, the shear strain rate at the inclined crack occurring point is transformed to the uni-axial tensile strain rate. Next, the increasing factors of tensile strength of the concrete and the yield strength of the shear reinforcement are calculated. Lastly these factors are multiplied to Vu and Vs respectively.

3. COMPARISON BETWEEN THE CALCULATED VALUES AND EXPERIMENTAL RESULTS IN OTHER STUDIES

The experimental results6)7) for simply supported plates or column-slab structures were compared with the calculated values by the present evaluation method. These experiments include dynamic and static loading test, and plates with and without shear reinforcement. The shear reinforcement ratio varies from 0.214% to 0.857%. The test results of the plates of which failure mode could be considered as bending mode were excluded. In the test shown in Ref. 6, the slab was supported at the center by column, and pushed at the circumferential area, therefore the shape of specimen and loading method was different from the other experiments.

As for dynamic loading tests assuming that strain of concrete reaches the shear fracture strain level at the first peak of the load-time history (shown in Fig.3), which is obtained by the experiments,and strain of shear reinforcement reaches yield strain level at the second peak,each strain rate is calculated. Based on the strain rates, the dynamic increasing factors of the strengths were determined.

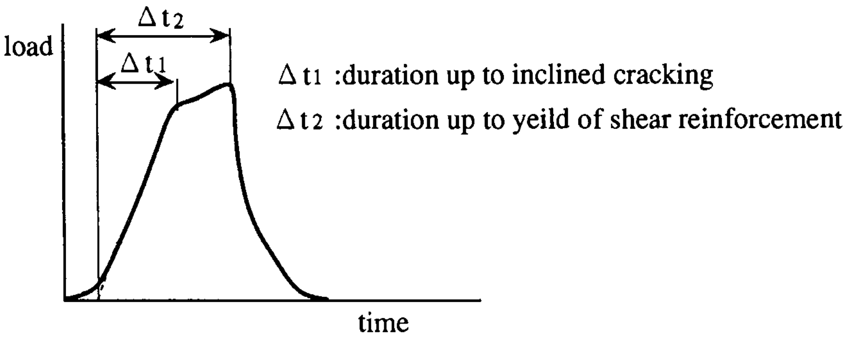

Fig.3 Typical load-time history of slab with shear reinforcement subjected to rapid loading

The comparison between experimental and calculated values of the ultimate shear strength for the static loadings is shown in Table 1 and Fig.4, and for the comparison in dynamic loadings are shown in Table 2 and Fig.5. Though the calculated values were slightly smaller than obtained values in the experiment of the plate supported at the center by column [6], both values agree well each other.

4. CONCLUSION

The evaluation method of the the ultimate punching shear strength subjected to rapid loading was suggested, taking account of the scale effect for slab thickness, the effect of the shear reinforcement and the strain rate effect of the material strength. Using this method, past experimental results were evaluated. As a result, the calculated results agreed well with the experimental results.

We believe following items will be important themes, which we intend to deal with hereafter.

(1) To verify the reliability of the equation applying to more experimental results.

(2) To take account of the effect of prestressing force.

We believe that the ultimate shear strength increases when compressive force by prestressing etc. are applied to the plates, and it is desirable to take account of the effect on the equation.

This study is a part of cooperative study conducted by The Kansai Electric Power Co., Hokkaido Electric Power Co., Shikoku Electric Power Co., Kyushu Electric Power Co., The Japan Atomic Power Co., and Mitsubishi Heavy Industries Ltd.

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Table-1 Comparison of experimental and calculated results(static loading)

Investigation	Specimen	Effective depth(cm)	p (%)	p_w (%)	u (cm)	Experimental strength(tf)	Calculated strength(tf)	$\frac{\text{Exp.}}{\text{Cal.}}$
T.Yamada (Ref.6)	K1	17.2	1.53	0.	30.×30.	67.1	68.9	0.97
	K2	17.2	1.53	0.25	30.×30.	96.9	70.5	1.38
	K3	17.2	1.53	0.50	30.×30.	120.7	87.4	1.38
	K4	17.2	1.53	0.55	30.×30.	117.7	88.5	1.33
E.Limberger et. al. (Ref.8)	V303	14.5	1.49	0.	ϕ27.	56.1	49.9	1.12
	V306	20.5	0.73	0.	ϕ27.	56.6	52.5	1.08
	V318	20.5	0.73	0.453	ϕ16.	62.7	75.5	0.83
	V321	20.5	0.73	0.	ϕ27.	65.3	73.0	0.89
	V322	20.5	0.73	0.250	ϕ27.	68.4	77.3	0.89
	V405	14.5	0.942	0.	ϕ16.	44.6	39.8	1.12
	V407	14.5	0.942	0.857	ϕ16.	79.0	71.4	1.11
	V409	14.5	0.603	0.857	ϕ16.	70.0	68.5	1.02
	V411	14.5	0.942	0.857	ϕ16.	75.2	71.7	1.05
H.Saito et. al. (Ref.9)	Flat slab(A)	9.3	0.611	0.	15.×15.	17.8	13.6	1.30
	Flat slab(B)	10.2	0.251	0.	15.×15.	12.0	11.7	1.03
	Flat slab(C)	5.2	0.615	0.	15.×15.	6.3	5.9	1.06

Table-2 Comparison of experimental and calculated results(dynamic loading)

Investigation	Loading condition	Specimen	Effective depth(cm)	p (%)	p_w (%)	u (cm)	Experimental strength(tf)	Calculated strength(tf)	$\frac{\text{Exp.}}{\text{Cal.}}$
W.Jonas et. al. (Ref.7)	impact loading	II/4	62.	0.865	0.502	ϕ75.	1336.	1249.	1.07
		II/6	62.	0.865	0.502	ϕ75.	1397.	1204.	1.16
		II/7	62.	0.865	0.246	ϕ80.	1138.	846.	1.35
E.Limberger et. al. (Ref.8)	rapid loading	V401	14.5	0.942	0.	ϕ16.	73.5	65.0	1.13
		V402	14.5	0.942	0.214	ϕ16.	60.4	58.0	1.04
		V403	14.5	0.942	0.857	ϕ16.	71.3	86.9	0.82
		V404	14.5	0.942	0.	ϕ16.	52.9	51.8	1.02
		V406	14.5	0.942	0.857	ϕ16.	96.7	100.5	0.96
		V408	14.5	0.942	0.	ϕ27.	84.0	87.5	0.96
		V410	14.5	0.603	0.857	ϕ16.	82.7	90.5	0.91
		V412	14.5	0.339	0.857	ϕ16.	76.5	88.2	0.87
H.Saito et. al. (Ref.9)	rapid loading (low speed)	flat slab(A)	9.3	0.611	0.	15.×15.	19.0	16.5	1.15
		flat slab(B)	10.2	0.251	0.	15.×15.	12.7	12.9	0.98
		flat slab(C)	5.2	0.615	0.	15.×15.	7.2	6.6	1.08
	rapid loading (high speed)	flat slab(A)	9.3	0.611	0.	15.×15.	24.0	23.3	1.03
		flat slab(B)	10.2	0.251	0.	15.×15.	16.9	19.1	0.89
		flat slab(C)	5.2	0.615	0.	15.×15.	10.8	10.0	1.08

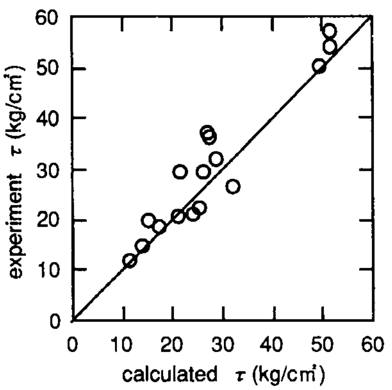

Fig.4 Comparison of experimental and calculated results(static loading)

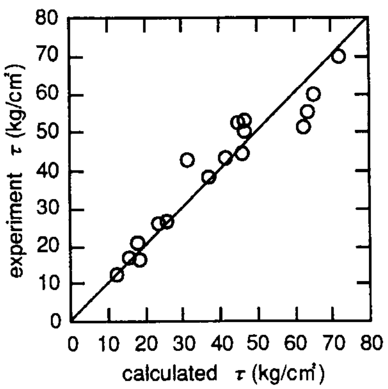

Fig.5 Comparison of experimental and calculated results(dynamic loading)