Study of Punching Shear Strength of Concrete Slabs under a Moving Load

Hokkaido Univ. SAKURA Keitaro
Hokkaido Univ. Member UEDA Tamon

1. INTRODUCTION

Recently, many experiments on slabs have been carried out. It was clarified through the experiments that fatigue strength of slabs under a moving load can be 50% as large as that under a fixed point loading and the mechanism of damage accumulated in concrete slab is identified by a wheel running test. So far, some *S-N* models of punching shear strength under a moving load have been proposed. In this study, a new *S-N* model of punching shear strength of concrete slabs was developed based on these previous results.

2. SPECIMENS PREPARATION

The test specimens[1][2][3][4][5][6] used in this experimental study are summarized in **Table 1**. DR to RC16 specimens are RC slabs, Z and FTS specimens are composite slabs, whose steel plates are 0.16cm thick, and BARD specimen is a half pre-cast prestressed concrete slab. Thickness of IR to IS specimens is 7.2cm, which is smaller than the minimum thickness of 16cm established by the Specifications for Highway Bridges, and those of the other specimens are over 16cm thick. The wheel running test machine has 2 types, crank type or self-running type, and loading patterns are 2 types, loading at constant load or that at gradually increasing load, but these differences are not specially considered in calculation.

Table 1. Specification of test specimens

Specimen	width × length × thickness (cm^3)	effective span (cm)	reinforcement ratio (main reinf't direction) tension side	compression side
DR	200 × 300 × 19	180	0.01379	0.00690
RC39	280 × 450 × 19	250	0.00843	0.00422
IR	90 × 310 × 7.2	80	0.01022	0.00511
IS	90 × 310 × 7.2	80	0.01022	0
ID	90 × 310 × 7.2	80	0.01022	0.01022
OR	90 × 310 × 7.2	80	0.01022	0.00511
OS	90 × 310 × 7.2	80	0.01022	0
RC47	280 × 450 × 20	250	0.01472	0.00756
RC8o	280 × 450 × 25	250	0.00940	0.00652
RC8n	280 × 450 × 25	250	0.00940	0.00515
RC19	280 × 350 × 19	250	0.00887	0.00461
RC16	280 × 350 × 16	250	0.01091	0.00567
Z	280 × 450 × 24	250	0.02129	0.01039
FTS	280 × 450 × 25	250	0.01570	0.00867
BARD	280 × 450 × 20	250	0.01047	0.02297

3. PROPOSED EQUATION

The followings are the process of fatigue damage on concrete slab under a running load.

① Cracks occur in one direction (the direction of main reinforcement)

② Cracks occur in another directions (the direction of distribution reinforcement) too.

③ Cracks develop as a tortoise shell.

④ Corners of the spaces among cracks fail and cracks are slit up.

⑤ Concrete is splitting and concrete slab has a hole on the surface.

In this process, it has been known that a part of slab becomes a beam-like form in the direction of main reinforcement, which influences punching shear strength of the slab under fatigue loading. It is considered that shear strength equation of RC beam can be applied to slab by assuming the part of slab to be a beam. The following is the shear strength equation[7] of RC beam.

$$V_c = 0.20 f'_c{}^{1/3} (100\rho_t)^{1/3} (d/1000)^{-1/4} (0.75 + 1.4d/a) b_w d \qquad \cdots\cdots (1)$$

Where,

f_c' : Concrete compressive strength (N/mm^2)

ρ_t : Tension reinforcement ratio

a : Distance from loading plate to supporting point (mm)

b_w : Web width (mm)

d : Effective depth (mm)

In order to apply Eq. (1) to predict the fatigue punching shear strength, definition of effective width is necessary. Comparison of results calculated by Eq. (1) with experimental results in the previous studies indicates that some modifications of Eq. (1) are necessary.

(1) Effective width

It is important that effective width b_{we} is newly adopted in Eq. (1) instead of web width b_w. Proposed effective width is similar to that in Matsui equation[8] and finally assumed to be $b_{we} = b + 8d_d$ (b : length of loading plate in the direction of distribution reinforcement, d_d : effective length in the direction of distribution reinforcement) in this equation. Applying Eq. (1), the *S-N* model is shown in Fig. 1. It shows that specimens with thickness over the minimum thickness of 16cm and specimens with thickness under it separate out. Since practically cases over the minimum thickness were more important, the proposed equation in this study is limited to the cases over 16cm thickness.

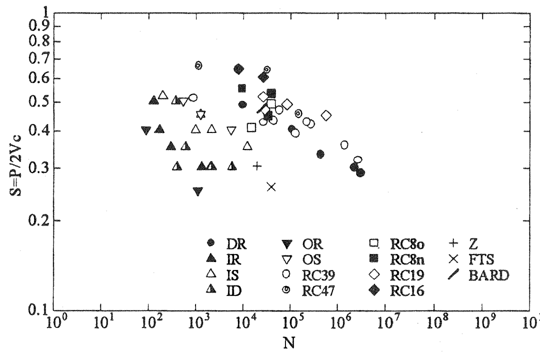

Fig. 1 *S-N* model by Eq. (1)

(2) Compression reinforcement

As for specimens whose thickness is under the minimum thickness of 16cm (7.2cm thick in all the cases) showed by triangle in Fig. 1, IR, ID and OR specimens including compression reinforcement and IS and OS specimens not including it separate up and down. In order to correct the effect of compression reinforcement, the tendency that the increase of compression reinforcement drops fatigue strength is added to Eq. (1) by multiplying the coefficient $(1+100\rho_t')^{-1/4}$. The reason of the decrease in fatigue strength by increasing compression reinforcement is firstly, the decrease in effective shear section and secondly, the increase of tensile stress and initial crack by shrinkage of concrete which is caused by confining compression reinforcement. The previous thesis[9] on static shear strength of beam also shows that the existence of compression reinforcement reduces shear strength and rapidly magnifies the width of shear crack in case that shear force is carried by concrete in truss mechanism. On the other hand, there are no available data that can show the effect of compression reinforcement. In this study, emphasis is made to the tendency obtained by specimens with 7.2cm thickness and thus the effect of compression reinforcement was considered.

(3) Composite slab

As for composite slabs Z and FTS, steel and concrete are considered in the same way as RC slab to calculate shear strength, assuming that the steel plate acts as tension reinforcement. As a result, in **Fig. 1**, the calculated points are below the *S-N* curve of RC slab. This is because the role of steel plate as tension reinforcement is considered a little in shear strength.

(4) Half pre-cast prestressed concrete slab (PC-PCa slab)

PC-PCa slab BARD, which consists of two concrete, pre-cast concrete and cast in place concrete, is considered as cast in place concrete in strength calculation. The effect of prestress is considered by multiplying the coefficient $\beta_n = 1+2M_o/M_u$ that is shown in JSCE Standard Specifications for Concrete Structures. The result plotted in **Fig. 1** shows a good agreement with *S-N* curve of RC slab, and it confirms the applicability of the proposed equation to the half pre-cast prestressed concrete slab.

(5) The proposed equation

The equation of punching shear strength of concrete slab under a moving load, which is derived by the above-mentioned process, is given by the following equation.

$$V_c = 0.20 f'_c{}^{1/3}(100\rho_t)^{1/3}(1+100\rho'_t)^{-1/4}(d/1000)^{-1/4}(0.75+1.4d/a)b_w d \quad \cdots\cdots(2)$$

$$b_w = b + 8d_d$$

Where,

f_c' : Concrete compressive strength (N/mm^2)

ρ_t : Tension reinforcement ratio

ρ_t' : Compression reinforcement ratio

a : Distance from loading plate to supporting point (mm)

b_w : Effective width (mm)

d : Effective depth for the direction of main reinforcement (mm)

b : Length of loading plate in the direction of distribution reinforcement (mm)

d_d : Effective depth for the direction of distribution reinforcement (mm)

(6) *S-N* model

S-N model, in which abscissa is running load cycle *N* and ordinate is load ratio *S* (= running load *P* / strength $2V_c$), with both axes in logarithm scale, is shown in **Fig. 2**. It is got by applying data shown in **Table 1** except for specimens with 7.2 cm thickness to **Eq. (2)**. **Eq. (3)** is a best-fit *S-N* curve equation that **Fig. 2** indicates.

$$\log S = -0.08988 \log N + \log 1.38291 \qquad \cdots\cdots\cdots\cdots (3)$$

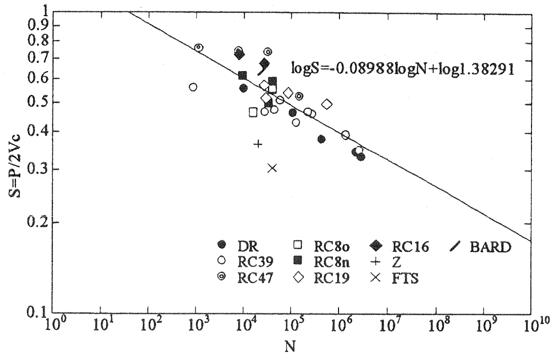

Fig. 2 *S–N* model by Eq. (2)

4. CONCLUDING REMARKS

(1) By applying shear strength equation of RC beam to concrete slab, which considers shear span ratio, we can propose the equation of punching shear strength of concrete slab under a moving load and the *S-N* model equation based on it.

(2) On concrete slab with thickness over 16 cm, the effective width is considered to increase linearly with the effective depth in the direction of distribution reinforcement.

(3) The increase of compression reinforcement drops fatigue strength. However it is necessary to study the effect of compression reinforcement more because there are few data to indicate it now

(4) The point of composite slab plotted on *S-N* diagram is lower than that of RC slab due to ineffectiveness of steel plate as tension reinforcement in shear strength development.

(5) The proposed equation can be applied to half pre-cast prestressed concrete slab in strength calculation by introducing the coefficient $\beta_n = 1 + 2M_o / M_u$.

REFERENCES

1. MAEDA, Y., and MATSUI, S., "Fatigue of Reinforced Concrete Slabs under Trucking Wheel Load", Proceedings of JCI, Vol.6, 1984, pp.221-224. (in Japanese)
2. JSCE, Steel Structure Committee, Investigating Research Subcommittee on Slabs of Steel Bridges, "New Technology and Performance-based Design of Slabs of Highway Bridges", Oct. 2000, pp.3-41. (in Japanese)
3. SONODA, K., and HORIKAWA, T., "Low Cycle Fatigue Characteristics of Bridge Deck RC Slabs under the Repetition of Wheel Loads", Proceedings of JSCE, No.390/V-8, Feb. 1988, pp.97-106. (in Japanese)
4. MATSUO, S., YOKOYAMA, H., HINO, K., and HORIKAWA, T., "Fatigue Properties of Existing RC Slabs under Wheel Running Machine with Pneumatic Tire", Proceedings of 2nd Symposium on Decks of Highway Bridges, pp.161-166. (in Japanese)
5. PWRI, "Proceeding of Joint Study", No.221, Mar. 1999, pp.15-53. (in Japanese)
6. PWRI, "Proceeding of Joint Study", No.250, Nov. 2000, pp.109-133. (in Japanese)
7. NIWA, J., YAMADA, K., YOKOZAWA, K., and OKAMURA, H., "Re-evaluation of the Equation for Shear Strength of Reinforced Concrete Beams without Web Reinforcement", Proceedings of JSCE, No.372/V-5, Aug. 1986, pp.167-176. (in Japanese)
8. MATSUI, S., "Fatigue Strength of RC-slabs of Highway Bridges by Wheel Running Machine and Influence of Water on Fatigue", Proceedings of JCI, Vol.9, No.2, Jul. 1987, pp.627-632. (in Japanese)
9. SAWAMURA, S., MARUYAMA, K., and MAEKAWA, K., "Shear Cracking Behaviors of Reinforced Concrete Simple Supported Beams", Proceedings of JCI, Vol.6, 1984, pp.481-484. (in Japanese)