Effect of In-Plane Shear Stress on Punching Shear Strength of Reinforced Concrete Wall Element

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ABSTRACT

This paper presents the results of the test conducted to clarify what effects the in-plane shear stress has on the punching shear strength of the wall. Three specimens that represent the penetration area of the concrete containment in a nuclear power plant were provided. The maximum value of the in-plane shear stresses was differently given to each of the specimens. An additional punching shear force was applied when the in-plane shear stress reached the given maximum value. The effect of the in-plane shear stress on the punching shear strength was investigated by comparing the punching strength of each specimen which had a different in-plane shear stress.

The conclusions are as follows:

(1) The punching shear strength decreases slightly due to the existence of the in-plane shear stress, provided that the in-plane shear stress is below $0.15 \cdot f'_c$.

(2) The test results agree with other punching test results under the condition of the biaxial tension.

1. INTRODUCTION

A concrete containment in a nuclear power plant necessarily has a few circular openings for penetrations of main steam pipes, which are restrained at the openings. Therefore, it may be expected that the concrete wall around the openings is subjected simultaneously to a tangential (in-plane) shear force caused by the gravity load and to a punching (out-of-plane) shear force from the pipes in case of an earthquake. The purpose of this study is to clarify the effects of the in-plane shear stress on the punching shear strength of the wall in such a case.

2. TEST PROGRAM

2.1 Specimen

Three 1/6 scale test specimens were made in such a way that an actual penetration area in the concrete containment could be simulated. The element of a cylindrical containment wall (outer shield wall) was simplified to a plane wall element. Each of the specimens had an H-shaped cross section of which the web dimension was 125 cm x 125 cm

(49 in.) with 24 cm (9.4 in.) thickness and had a circular opening at the center of the web. The diameter of the opening was 20 cm (7.9 in.). In order to apply the lateral load, rigid slabs were arranged at the top and the bottom of the specimen, as shown in Fig. 1. The arrangement of reinforcing bars and the details of the penetration area were so determined as to simulate an actual structure. The diagonal reinforcement was provided around the opening in addition to the vertical and the horizontal reinforcements. The compressive strength of the concrete (f'_c) was 288 kg/cm^2 (4.1 ksi) and the yield strength of the reinforcing bar (f_y) was 4,100 kg/cm^2 (58.3 ksi). The reinforcing steel ratio (ρ) of all specimens was 1.14 % for the vertical and the horizontal directions respectively.

2.2 Loading and Measurement

The outline of the loading setup is shown in Fig. 2. Using two hydraulic actuators with a loading capacity of 100 ton, alternating lateral loads were applied to the top slab of two of the test specimens respectively, so that the in-plane shear stresses were given in the web section (Fig. 2a). No lateral load was imposed on the third specimen. Thus, the maximum value of the in-plane shear stresses was differently given to each specimen, i.e., $0.15 \cdot f'_c$, $0.10 \cdot f'_c$, 0. The maximum value of the in-plane stresses was determined with reference to the shear stresses that were assumed to be induced by earthquakes in the design of an actual structure. Accordingly, the test specimens were cracked diagonally in the lateral loading except the third specimen with no in-plane shear stress.

When the in-plane shear stress reached the given maximum value, the punching shear force was applied monotonically to the opening of the specimen with another actuator, sustaining the maximum horizontal in-plane displacement. The fourth actuator was provided to restrain the out-of-plane displacement of the top slab (Fig. 2b).

Deflections were measured with a view to obtaining the deflection modes of the specimen. Strains of representative reinforcing bars were also measured.

3. TEST RESULTS

The cracking patterns of the web walls at the ultimate state are shown in Fig. 3. The dotted lines indicate the cracks caused by the lateral (in-plane) loading prior to the punching load, and the full lines are the ones caused by the punching shear loading. Two of the specimens (No.1, No.2) were diagonally cracked in the lateral loading and had few cracks newly induced by the punching shear loading. The third specimen (No.3), with no in-plane shear stress, had a typical cracking pattern induced by the punching shear loading. In Fig. 4, the load-displacement relations of out-of-plane direciton are recorded, up to the point when the shear cone failures are supposed to have started judging from the deflection modes of the specimens. It is indicated that the punching shear strength decreases slightly and the out-of-plane displacement at the ultimate state becomes a little larger, with the increase of in-plane shear stress. This fact means that the out-of-plane stiffness drops due to the diagonal cracks, but that the punching shear strength does not decrease so much. In other words, the diagonal cracks do not lead to a significant reduction in the punching shear strength.

The principal values of the test results are listed in Table I, and are compared with the predicted strength calculated by eq.(1) given in ACI Code [1].

$$V_u = 4\sqrt{f_c'}\cdot b_o\cdot d \qquad (1)$$

where b_o is the perimeter of the critical section around the opening and d is the effective depth of the web.

4. COMPARISON OF THE RESULTS WITH OTHER TEST RESULTS

As shown in Table I, in spite of the reduction of the shear strength, the test results indicate larger values than those given by eq.(1). One of the reasons for the difference lies in the fact that eq.(1) gives the conservative values for design purposes.

White, Gergely and Jau [2] discussed the method to predict the punching shear strength of biaxially tensioned reinforced concrete wall elements. Thirty punching tests under the condition of the biaxial tension were conducted and it was pointed out that the reduction in the punching shear strength caused by the biaxial tensile stresses was not so significant as given by the equations in ASME Code [3]. The results of thirty punching test are plotted in Fig. 5. Based on their test results, eq.(2) and eq.(3) were introduced and recommended to predict the actual strength and the allowable capacity of the biaxially tensioned wall elements, respectively.

$$V_u = (6-1.5\cdot f_s/f_y)\sqrt{f_c'}\cdot b_o\cdot d \qquad (2)$$

$$V_u = (4-f_s/f_y)\sqrt{f_c'}\cdot b_o\cdot d \qquad (3)$$

where f_s is the tensile stress of the reinforcing bar and f_y is the yield strength of them.

Because of the difference between the in-plane loading conditions, it is not appropriate to compare the test results shown in Table I directly with Fig. 5. Then the in-plane shear stresses are converted into equivalent biaxial tensile stresses by following two methods. It is assumed in both method that the levels of the in-plane shear stresses can be evaluated from the tensile stresses of the reinforcing bars as in case of the test under the condition of the biaxial tension.

(Method 1)

The in-plane shear stress in the cracked section is transferred exclusively by the tensile stress in the orthogonal reinforcing bars. Then the equivalent biaxial tensile stresses in the reinforcements are calculated as $f_s=v/\rho$, where v is in-plane shear stress and ρ is the reinforcing steel ratio.

(Method 2)

The levels of the shear stresses can also be evaluated from the observed tensile strains of the reinforcements. Then the equivalent tensile stress is given as $f_s=E_s\cdot\varepsilon_s$, where E_s is the modulus of elasticity and ε_s is the mean value of the observed tensile strains of the reinforcements.

The converted test results are plotted in Fig. 5 and are compared with the data of White et al. As shown in Fig. 5, the punching shear strength of the first two test specimens (No.1, No.2), which have many cracks caused by the in-plane stresses, is reduced only to 80 % of that of the nonstressed specimen (No.3). And it could be stated that, as regards the tendency of reduction in the punching shear strength caused by in-plane stress, there is a similarity between our results and those of White et al. Such an evaluation, however, cannot be definite, mainly due to the insufficient number of specimens in our tests.

Consequently, for the time being, it would be preferable to predict the punching shear capacity of the wall subjected to the in-plane shear stress using eq.(2) and eq.(3), by evaluating the in-plane stress as equivalent biaxial tensile stresses.

5. CONCLUSIONS

The punching shear test results of the three specimens subjected to the in-plane shear stress up to $0.15 \cdot f_c'$ have concluded that the punching shear strength decreases slightly due to the existence of the in-plane shear stress.

The equations given in the ASME Code are available to predict the punching shear strength of walls subjected to the in-plane stress, but they tend to overestimate the effect of the in-plane stress, as White et al. pointed out. The punching shear strength can be predicted more exactly by using the equations proposed by White et al., provided that the in-plane shear stress can be evaluated appropriately as biaxial tensile stresses.

Therefore, for the time being, eq.(2) and eq.(3) are recommended as the method to predict the punching capacity of walls subjected to the in-plane shear stress, after a reasonable conversion of the in-plane shear stress into equivalent biaxial tensile stresses.

REFERENCES

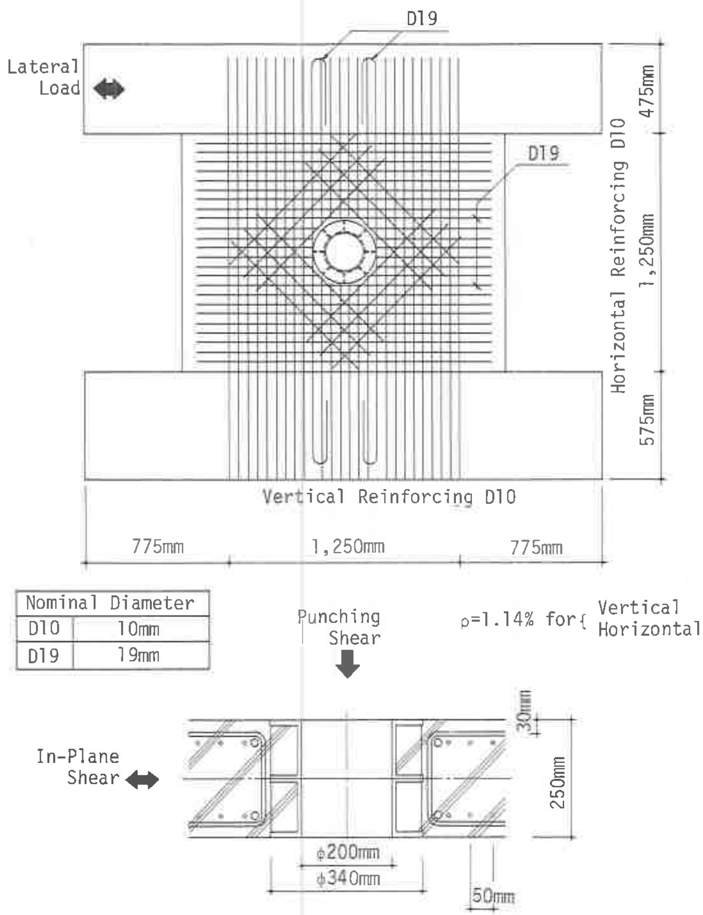
[1] ACI Building Code Requirements for Reinforced Concrete, ACI 318-83.

[2] White, R. N., Gergely, P., Jau, W. C., "Peripheral Shear Strength of Biaxially Tensioned Reinforced Concrete Wall Elements", Nuclear Engineering and Design 69, (1982).

[3] ASME Boiler and Pressure Vessel Code, Section III, Division 2, (1983).

Table I Test Results

Test Specimen		No.1	No.2	No.3
Punching Strength	ton kip	100.2 220.9	100.4 229.3	124.8 275.1
[Calculated Strength by eq.(1)]	ton kip		[69.6] [153.4]	
Punching Stress at the Ultimate	kg/cm^2 psi	25.9 368.2	26.9 382.3	32.3 458.7
Deflection at the Ultimate	mm	1.4	1.5	1.2
In-Plane Shear Stress		$0.15 \cdot f'_c$	$0.10 \cdot f'_c$	0



Nominal Diameter	
D10	10mm
D19	19mm

Fig. 1 Test Specimen

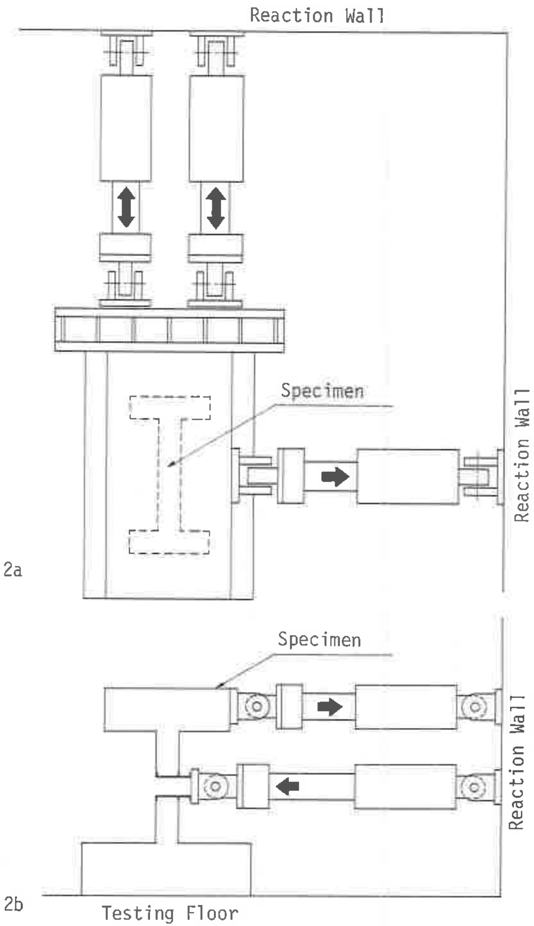


Fig. 2 Loading Setup

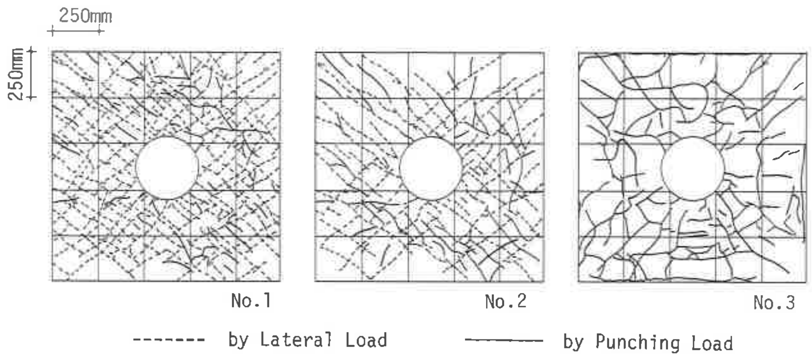


Fig. 3 Cracking Pattern at the Ultimate State

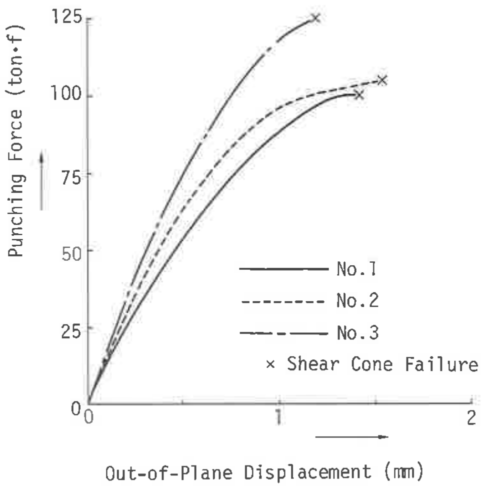
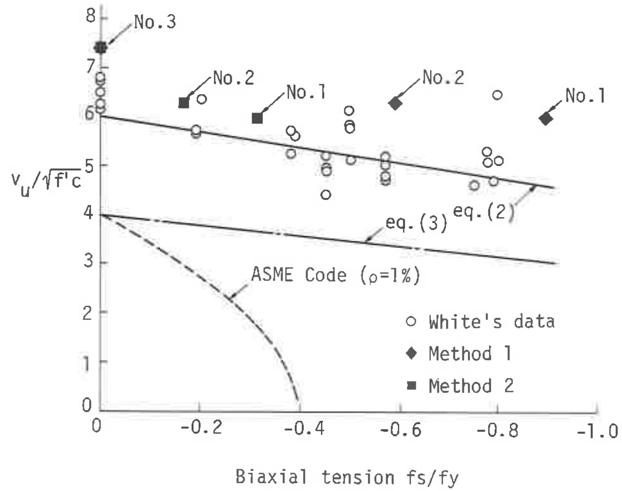


Fig. 4 Load-Displacement Relation



$v_u = 4\sqrt{f'c}\,\sqrt{1+fm/4\sqrt{f'c}}$ (ASME Code)

$v_u = (6-1.5\cdot fs/fy)\sqrt{f'c}$ eq.(2)

$v_u = (4-fs/fy)\sqrt{f'c}$ eq.(3)

(eq.(2) and eq.(3): White et al.)

v_u : Punching Shear Stress (psi)
f'c : Compressive Strength of Concrete (psi)
fm : Membrane Tensile Stress (=ρ·fs)
fs : Tensile Stress of Reinforcing Bar
fy : Yield Strength of Reinforcing Bar

Fig. 5 Comparison of Test Results