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STUDY ON LOAD-DEFLECTION CHARACTERISTICS OF HEAVILY REINFORCED CONCRETE SHEAR WALLS

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SUMMARY

The purpose of this study is the quantitative evaluation of the load-deflection characteristics of the heavily reinforced concrete shear walls by the experimental and analytical studies. Twenty seven specimens of shear walls, adopting five parameters, are employed. The formula to estimate the maximum shear strength of shear walls is proposed based on the experimental and analytical studies. The shear deformation at the maximum shear strength is evaluated by the experimental study. The skeleton curve and the hysteresis loop are proposed as the tri-linear model and the non-dimensional cubic equation model, respectively.

INTRODUCTION

A nuclear power reactor building consists of reinforced concrete shear walls which are heavily reinforced and bearing the axial stress. Some experimental studies related to these heavily reinforced concrete shear walls have been carried out in this decade and the load-deflection characteristics have been made clear, but have not been quantitatively estimated because the experimental data are not enough.

In this paper, the authors wish to introduce the outline of the experimental study and the load-deflection characteristics estimated by the experimental and analytical studies on heavily reinforced concrete shear walls.

SPECIMENS AND PARAMETERS

The contents of twenty seven specimens are shown in Table 1. The specimens employed in this study are the single storied and single bay shear walls. They consist of the shear wall of 8cm in thickness, the rectangular girder of 30cm × 30cm on the shear wall and the rectangular columns 30cm × 30cm at the both sides of the shear wall. The span length of shear wall is 200cm and its height varies depending on shear span length ratio. The shape of typical specimen is shown in Fig. 1. The following five parameters are employed as those will effectively contribute to the load-deflection characteristics of concrete shear walls.

(1) Reinforcement ratio of shear wall(p_w) ; from 0% to 2.8%
(2) Axial stress(σ_0) ; 0.0, 20.0 and 40.0kg/cm^2
(3) Shear span length ratio(M/QD) ; 0.4,0.6 and 0.8
(4) Compressive strength of concrete(Fc) ; 240 and 360kg/cm^2
(5) Longitudinal reinforcement ratio of column(p_g) ; 1.2 and 2.0%

LOADING AND MEASUREMENT SYSTEM

The loading devices are shown in Fig. 2. The computer controlled actuators with servo-mechanism are applied to this experimental study. As the horizontal loading, the alternately cyclic loading schedule previously prepared as the files in the computer are applied. The axial stress is kept as the constant value uniformly distributed over the cross sectional area of the shear wall and columns by the actuator.

The displacements and deformations of specimens and the strains of reinforcing bars and of surface of concrete are automatically aquired and stored in the computer system.

Table 1 Specimens

p_w(%) / M/QD	0	0.3	0.6	0.8	1.2	1.6	2.0	2.4	2.8
0.4			○		○		○		
0.6	△○□	○	△○□ ◇	○	△○□ ◇	○	△○□▽ ◇	○	○
0.8			○		○		○		

△: σ_0=0kg/cm² ○,▽,◇: σ_0=20kg/cm² □: σ_0=40kg/cm²
▽: Longitudinal reinforcement ratio of column =1.2%
◇: Fc=240kg/cm² the others 360kg/cm²

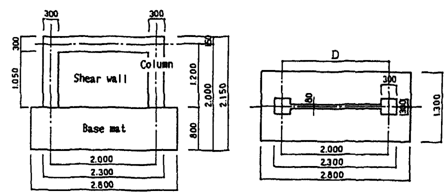


Fig. 1 Shape of a specimen (M/QD=0.6)

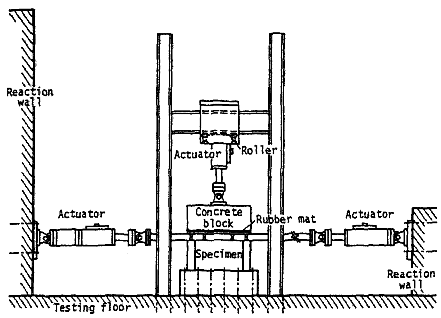


Fig. 2 Loading devices

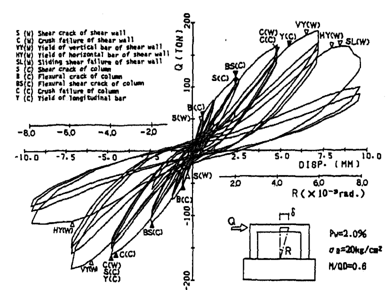


Fig. 3 Load-deflection characteristics

RESULTS AND DISCUSSIONS

The examples of load-deflection characteristics and crack distributions at final stage of specimens are shown in Fig. 3 and 4, respectively.

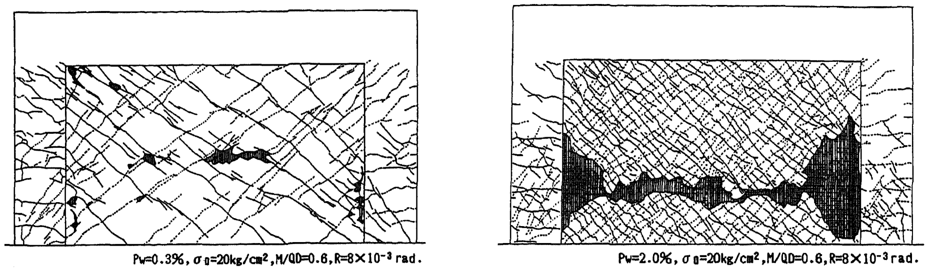
The shear crack on shear wall occurs first at the point of around(0.16∿0.48) $\times 10^{-3}$rad. of story drifts defined as the ratio of the horizontal displacement to the height. As the load or the horizontal displacement increases, a number of new shear cracks on shear wall and new cracks due to flexure and shear on columns occur and the cracks occured at the previous loading grow in size. Finally, the diagonal shear compression failure for poorly reinforced concrete shear walls and the sliding shear failure for heavily reinforced concrete shear walls occur as shown in Fig. 4(a) and 4(b), respectively.

The effect on the maximum shear stress by the reinforcements of shear wall is obtained as shown in Fig. 5. This effect is expressed by $p_w\sigma_y/2$ as shown by dotted line in Fig. 5, in which $p_w\sigma_y$ is less than $6.0\sqrt{Fc}$. This tendency is also obtained by the analytical study used the non-linear finite element method as shown in Fig. 5.

The effect on the maximum shear stress by axial stress is obtained as shown in Fig. 6. This effect is evaluated that the whole value of axial stress contributes to the maximum shear stress of shear walls without the specimens that the longitudinal bars of column and reinforcing bars of shear wall do not reach to yield stress. This effect is also obtained by the analytical study.

The tendency that the smaller shear span length ratio, the larger maximum shear stress, is obtained and this tendency is expressed by solid line as shown in Fig. 7. The inclination angle by this experimental study is represented by -4M/QD. This inclination angle closely agree with those obtained by the analytical study.

The maximum shear stress obtained by the experimental and analytical studies is shown normalized by $\sqrt{Fc}$ in Fig. 8. Comparing the results in dotted circles, the effect on the maximum shear stress of shear wall by compressive strength of concrete is evaluated by the normalization by $\sqrt{Fc}$.



(a) poorly reinforced specimen (b) heavily reinforced specimen

Fig. 4 Crack distributions at final stage

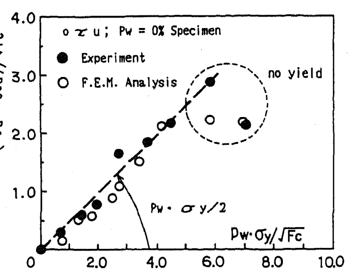


Fig. 5 Effect of reinforcements

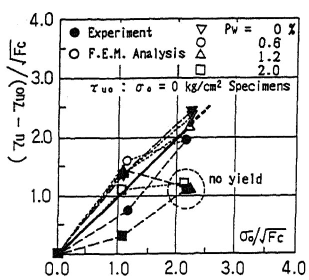


Fig. 6 Effect of axial stress

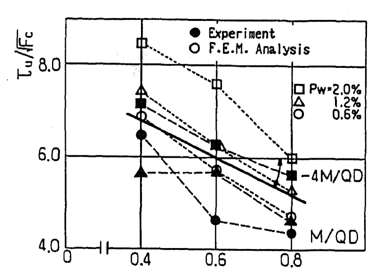


Fig. 7 Effect of shear span length ratio

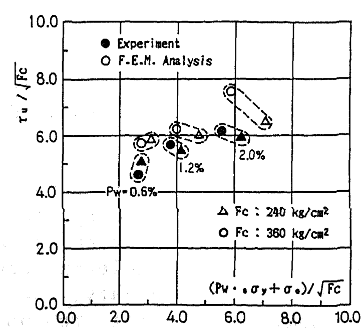


Fig. 8 Effect of compressive strength of concrete

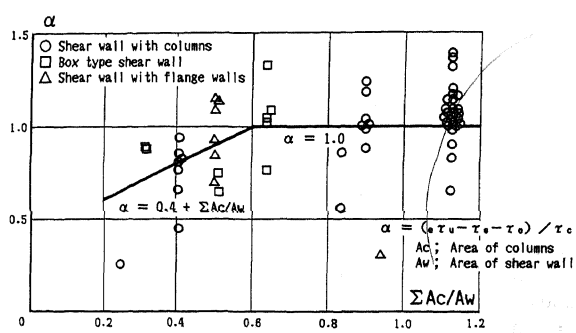


Fig. 9 Effect of columns and flange walls

ESTIMATION OF THE MAXIMUM SHEAR STRENGTH

The estimation of the maximum shear stress of shear walls is assumed to be expressed by the sum of the shear capacities carried by concrete(τ_c) and by reinforcement of shear wall(τ_s), and the effect by axial stress(τ_o) (Ref. 1). The confinement by columns and flange walls on the maximum shear stress of shear walls is assumed to have the effect on the shear capacity carried by concrete(τ_c) and is estimated by the solid line shown in Fig. 9. In this estimation, the experimental data of box type shear walls, shear walls with flange walls and shear walls with columns carried out by other researchers in Japan are also employed. Therefore, the equations, estimating the maximum shear stress of shear walls are expressed as follows.

$$Q_{max} = \tau_{max} \cdot t \cdot D \;,\quad \tau_{max} = \alpha \cdot \tau_c + \tau_s + \tau_o \tag{1}$$

$$\tau_c = 2.7\sqrt{Fc}(1.9 - 1.5M/QD) \tag{2}$$

$$\tau_s = p_w \sigma_y / 2 \;,\quad \tau_o = \sigma_o \tag{3}$$

$$\alpha = 0.4 + \Sigma Ac/Aw \;(\Sigma Ac/Aw \leqq 0.6) \quad \text{or} \quad \alpha = 1.0 \;(\Sigma Ac/Aw > 0.6) \tag{4}$$

in which t ; Thickness of shear wall
D ; Span length of shear wall
Ac ; Area of columns
Aw ; Area of shear wall(= t×D)
$p_w \sigma_y \leqq 6.0\sqrt{Fc}$ ($p_w \leqq 2.4\%$)
$\sigma_o = 0 \sim 40 kg/cm^2$, M/QD= 0.4 ∿ 0.8, Fc= 150 ∿ 600kg/cm^2
and $\Sigma Ac/Aw \geqq 0.2$

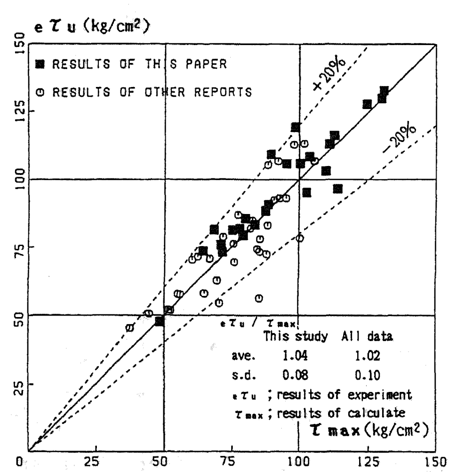


Fig. 10 Comparison of $_e\tau_u$ and τ_{max}

To investigate the adequacy of the maximum shear strength estimated by eq.(1), the maximum shear stress(τ_{max}) obtained by eq.(1) and the experimental results($_e\tau_u$) are compared in Fig. 10, in which the mark of ■ indicates the results of this study and ⊙ shows the results of the experimental study carried out by the other researchers in Japan (Refs. 2,3). τ_{max} closely agree with $_e\tau_u$ and almost of the experimental data adopted in this paper are included in ±20% of τ_{max}. The average values and standard deviations of $_e\tau_u/\tau_{max}$ are 1.04, 0.08 in this experimental study and 1.02, 0.10 for all data applied in this paper,respectively. The eq.(1) is anticipated to be one of the available equations to estimate the maximum shear strength of shear walls.

LOAD-DEFLECTION CHARACTERISTICS

The shear deformation angles(γ_{max}) at the maximum shear stress obtained by this experimental study are shown in Fig. 11 and the average value and standard deviation of them are 4.8×10^{-3}rad. and 0.6×10^{-3}rad., respectively.

The skeleton curve on the shear deformation obtained by this experimental study are shown in Fig. 12. Firstly, the envelope curves are estimated by the non-dimensional envelope ones which are normalized by the maximum shear stress and the shear deformation angle at that point, and the non-dimensional skeleton curve is modeled to the tri-linear type by the statistical analyses. Secondary, the skeleton curve is improved so as to simulate this experimental data more reasonably and is also modeled to the tri-linear type as shown by solid line in Fig. 12. The shear stress of the first point is given by $0.3\times\tau_{max}$(τ_{max}; the maximum shear stress) and the coordinate of the second point, ($0.5\times\gamma_{max}$, $0.8\times\tau_{max}$). The first point represents the stage which two or three shear cracks occur on heavily reinforced concrete shear walls or a diagonal shear crack on poorly reinforced concrete shear walls. The second point represents the stage which the partial compressive failure occurs on shear walls or the vertical reinforcing bar at central parts of shear walls reaches to the yield stress. The skeleton curve obtained by this experimental study and the modeled one are compared in Fig. 13. This modeled skeleton curve closely simulates the skeleton curve on the shear deformation obtained by this experimental study.

The hysteresis loops for shear deformation obtained by this experimental study are modeled by the following non-dimensional cubic equation.

$$Y = (1 - B)X^3 \mp AX^2 + BX \pm A \qquad (5)$$

in which $A = 3S/8$ (S ; Area of hysteresis loop)
B ; Inclination angle to Y axis

The values of S and B obtained by this experimental study are shown in Fig. 14 and 15, respectively. The mean values of S and B are evaluated as follows by the least square method and the experimental results of S and B are widely scattered around these mean values.

$$S = 0.24 + 16.0\times\gamma \qquad (6)$$
$$B = 0.50 - 76.0\times\gamma + 0.01\sigma_0 \qquad (7)$$

The skeleton curve proposed in Fig. 12, the hysteresis loop calculated by eq.(5) and the hysteresis loop obtained by the experiment are compared in Fig. 16. The hysteresis loop calculated by eq.(5) closely simulates the experimental result.

In this paper, the tri-linear model and the hysteresis loop calculated by non-dimensional cubic equation are proposed as the models to estimate the skeleton curve and the hysteresis loop for the dynamic response analysis of nuclear power reactor buildings.

CONCLUSION AND ACKNOWLEDGEMENT

Twenty seven specimens of reinforced concrete shear walls are employed in this study and the many effective results related to the load-deflection characteristics for shear walls are obtained. In this paper, the outline of this experimental study, the equations to estimate the maximum shear strength, the skeleton curve and the hysteresis loop on the shear deformation, and the shear deformation at the maximum shear strength are introduced.

The study presented herein is one of experimental works conducted in series under advices of a technical research committee organized in Building Research Promotion Association, Tokyo, Japan. The authors are indebted to members of the Committee for their valuable discussion.

REFERENCES

1. Chiba, O. et al.,"Experimental Study on Heavily Reinforced Concrete Shear Walls", 8th SMiRT Conference, H4/1*,131-136, Brussels, Belgium, (1985).
2. Chiba, O. et al.,"Load-Deflection Characteristics of Nuclear Power Building Structures"; Part 8-12,21-25,30 and 59-61, Trans. of AIJ, Extra in Japanese, Japan, (1983-1986).
3. Chiba, O. et al.,"Experimental Study on Heavily Reinforced Concrete Shear Wall",7th Japan Earthquake Engineering Symposium·1986, 1309-1314, Tokyo, Japan (1986).

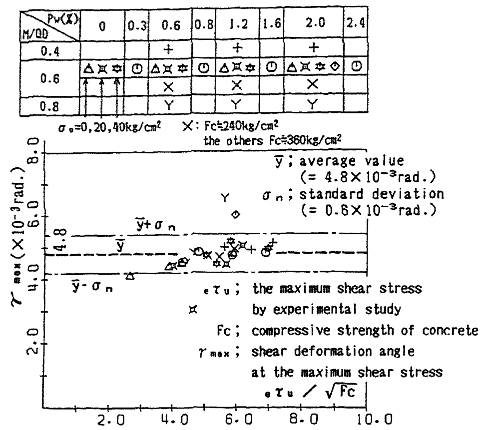


Fig. 11 Shear deformations at the maximum shear strength

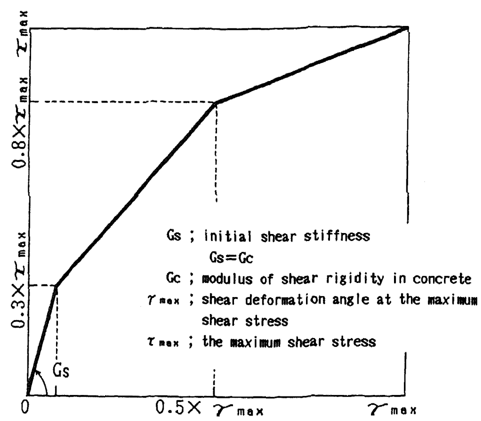


Fig. 12 Skeleton curve

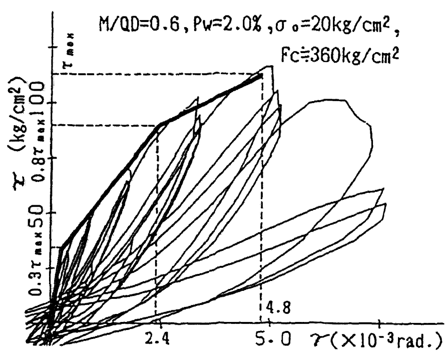


Fig. 13 Comparison of results of experiment and skeleton curve by modeling

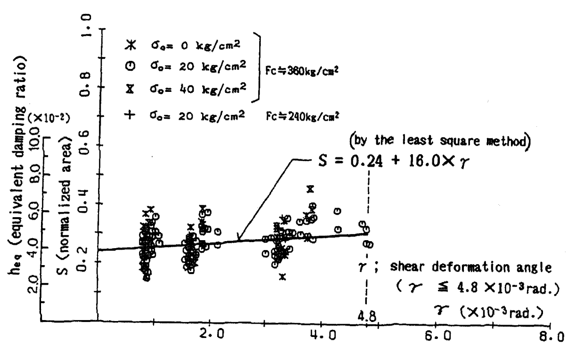


Fig. 14 Relationships between h_{eq} ,S and γ

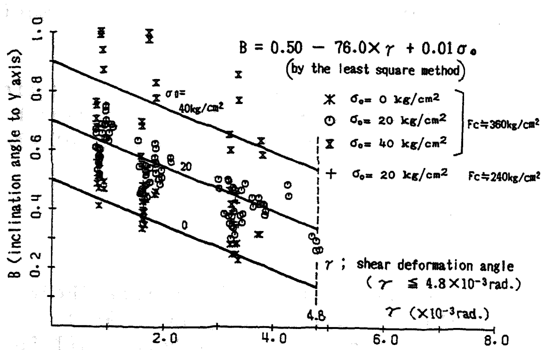


Fig. 15 Relationships between B and γ

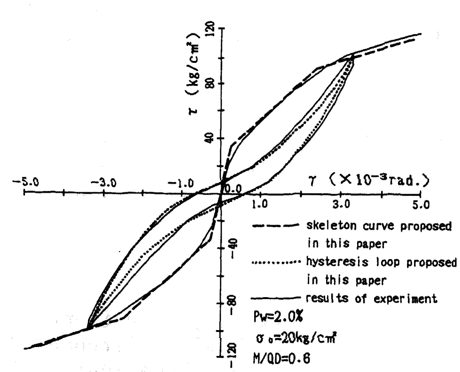


Fig. 16 Comparison modeled load-deflection characteristics with experiment ones