EXPERIMENTAL STUDY ON DYNAMIC PROPERTIES OF REINFORCED CONCRETE SHEAR WALLS

by

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SYNOPSIS

This investigation reports on the static hysteresis loop and the effect of the deflection and the number of loading cycles on the damping capacity and the degradation of the rigidity of reinforced concrete shear walls. The deflection at the cracking load and the ultimate load are not much influenced by the reinforcement ratio and the axial load of the columns. As the number of loading cycles increased at the constant amplitude of the loading, the rigidity reduces. The bigger the amplitude, the more remarkable this trend. The damping capacity is scarcely influenced by the deflection, the axial load and the wall reinforcement ratio. Its value reduces rapidly within several cycles of the repeated loading and takes about 0.03.

1 INTRODUCTION

In case of making earthquake response analyses of building structures, what sort of a restoring force characteristic would be assumed is one of the most important problems. Due to the lack of sufficient data on dynamic properties of building structures for determining its restoring force characteristic, it is necessary to examine the dynamic properties obtained from the experimental work.

We had made the dynamic tests of reinforced concrete frames and proposed the model of the restoring force characteristic of reinforced concrete frames. The purpose of this paper is to examine the restoring force characteristic of reinforced concrete shear walls and the effect of the deflection amplitude and the number of repeated loading cycles on the degradation of the equivalent rigidity and the damping capacity through the static cyclic loading tests.

2 TEST SPECIMEN

The test specimen was designed to represent a single-story shear wall of reinforced concrete. Fig. 1 shows the details of the model wall's

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configuration, reinforcement distribution, hoops and stirrup ties spacing. The column is 12 cm by 15 cm in dimensions, the beam 15 cm by 20 cm and the shear wall 60 cm by 88 cm, of which the thickness is 5 cm. The test specimens were cast in an upright position.

The deformed bars (D13), of which the nominal diameter was 13 mm, were used as the reinforcing steel of the columns and the beams. These bars had the yield strength of 3.9 t/cm^2 and the ultimate strength of 5.6 t/cm^2, which were determined by the standard laboratry tests. The annealed wire (#10), of which the nominal diameter was 3.2 mm, was used as the hoops, the stirrup ties and the wall reinforcement. The percentage of wall reinforcement of Specimen, WB-1, 2, 3, 4 and 5, is 0.25 percent in both the vertical and horizontal directions. And that of Specimen, WB-6, 7 and 8, is 0.5 percent. This annealed wire had the yield strength of 3.0 t/cm^2 and the ultimate strength of 4.1 t/cm^2.

The concrete was manufactured from normal Portland cement and natural aggregate. The maximum size of the gravel was 10 mm. The water-cement ratio of the concrete was 0.64 by weight. The slump was from 18 cm to 22 cm. The average ultimate strength of the concrete was approximately 160 kg/cm^2, as determined by the compression tests on 30 cm by 15 cm standard cylinder specimens according to the Japan Industrial Standard's specifications.

3 TESTING PROCEDURE

The test specimens were placed vertically in the loading rig. The concrete base block of the test specimen was firmly fastened to the extremely rigid testing floor with six anchor-bolts. These anchor-bolts were made of high strength steel and were 33 mm in diameter.

The lateral load was applied at the beam level and the axial load at the top of columns vertically. Oil jacks were used for these loads. Figs.2 and 3 show the schematic diagram and the photo of the whole veiw of the loading rig with a test specimen, respectively.

The deflection of the test specimen was measured at the beam level with a mechanical dial gage, which was marked in subdivisions of 0.01 mm. The lateral load, applied at the beam level, was monitored using a load cell instrumented with wire strain gages. The total axial load was monitored with the pressure gage of the oil jack. The axial load was mannually controled constant, even if the test specimen was made deflect.

Table 1 shows the loading method for each test specimen. As shown in Table 1, the several different deflection amplitudes and the number of loading cycles were determined beforehand. The number of cyclic loading predetermined was applied to the test specimen at the constant deflection amplitude predetermined.

The total axial load was determined like 0 t, 20 t and 40 t. The axial load of 20 t was equal to one-third of the compressive strength of the columns, which was the sum of the strength of concrete and that of reinforcing steel.

4 TEST RESULTS

HYSTERESIS LOOP Figs. 5, 6, 7, 8, 9 and 10 show the static hysteresis loops of Specimen, WB-1, 2, 3, 6, 7 and 8, respectively. The load-deflection curve of Specimen, WB-4, is shown in Figs. 5,6 and 7 by a dotted line. Fig. 4 shows the photo of Specimen, WB-7, after the whole loading, as a representative. Table 1 indicates the load and the deflection at the shear cracking load and the ultimate load of each test specimen.

The deflection of the wall at the shear cracking load is not much influenced by the wall reinforcement ratio and the axial load of the columns. And its value is about 0.4×10^{-3} rad.

The shear cracking load of the 0.5 percent wall reinforcement ratio specimen is slightly greater than that of the 0.25 percent. At the shear cracking load, the average shear stress of the 0.5 percent wall reinforcement ratio specimen is from 19 kg/cm^2 to 26 kg/cm^2, and that of the 0.25 percent is from 12 kg/cm^2 to 17 kg/cm^2.

The deflection of the wall at the ultimate load is not much influenced by the reinforcement ratio, the axial load of the columns, the load history and the number of the loading cycles. And its value is about 4×10^{-3} rad.

Compared among equal wall reinforcement ratio specimens, the ultimate load under the axial load is greater than that under the nonaxial load. At the ultimate load, the average shear stress of the test specimen under the axial load is from 58 kg/cm^2 to 69 kg/cm^2, and that under the nonaxial load from 36 kg/cm^2 to 48 kg/cm^2.

In the case of 0.25 percent wall reinforcement ratio specimens, the load-deflection curve of a monotonically loaded specimen is very similar to the envelope curve of static hysteresis loops of a specimen subjected to repeated load cycles within the deflection of 4×10^{-3} rad. Beyond this deflection, the rigidity of a specimen reduces rapidly, and then this envelopecurve shows a negative gradient.

EQUIVALENT RIGIDITY The rigidity of a specimen is defined as the slope of the line going through the peaks of the hysteresis loops. The effect of the number of loading cycles on the equivalent rigidity is shown in Figs. 11 and 12. As the number of cycles increases at the constant deflection amplitude, the rigidity of the specimen reduces. The bigger the deflection amplitude of the loading, the more remarkable this trend. If the deflection amplitude is greater than 4×10^{-3} rad., this trend is much more remarkable.

Fig. 11 shows the trend of the degrading rigidity of 0.25 percent wall reinforcement ratio and nonaxial load specimen. Shown a percentage of the rigidity at the 30th loading cycle to that at the first, the degrading ratio of the rigidity at the amplitude of 0.5×10^{-3} rad. is 85 percent, that of 2×10^{-3} rad. 75 percent and that of 4×10^{-3} rad. 60 percent.

Fig. 12 shows the effect of the axial load on the rigidity of 0.5 percent wall reinforcement ratio specimens at the amplitude 4×10^{-3} rad.

Even if the axial load was applied to the specimen, the degrading ratio of the rigidity is not much influenced and is from 50 percent to 70 percent.

DAMPING CAPACITY The equivalent viscous damping factor can be defined by the ratio of the dissipated energy to the potential energy. The dissipated energy is indicated by the area of the hysteresis loop and the potential energy by the position of the peak of the hysteresis loop.

The effect of the number of the repeated loading cycles on the equivalent viscous damping factor is shown in Figs. 13 and 14. Fig. 13 indicates the case of 0.25 percent wall reinforcement ratio and nonaxial load specimens. The equivalent viscous damping factor takes almost the same value and is scarcely influenced by the deflection amplitude. When the number of loading cycles reaches to 30 times, the damping factor takes about 0.03.

Fig. 14 shows the effect of the axial load on the equivalent viscous damping factor of 0.5 percent wall reinforcement ratio specimens. It can be seen that the axial load had scarce effect on the damping factor. The damping factor calculated from the 30th hysteresis loop takes about 0.03.

As the results mentioned above, the equivalent viscous damping factor is scarcely influenced by the deflection amplitude, the axial load and the wall reinforcement ratio. Its value reduces rapidly within several cycles of the repeated loading and takes about 0.03.

5 IDEALIZED MODELS FOR HYSTERESIS LOOPS

Two idealized models for the steady state hysteresis loops of reinforced concrete shear walls subjected to lateral loading reversals were proposed in this section.

MODEL BY POLYNOMIAL EQUATION The steady state hysteresis loop of reinforced concrete shear wall subjected to load reversals, based on the experimental results mentioned above, was simulated by the polynomial equation of the 5th order of the deflection. Expressed in the Eq. (1) was the simulated hysteresis curve, normarized by the maximum deflection and the maximum load and governed by the symmetrical rule of the figure about the origin of the co-ordinate.

$$y_b^a = \pm A + Bx \pm Cx^2 + Dx^3 \mp (A + C)x^4 + (1 - B - D)x^5 \quad (1)$$

where y_a and y_b are the upper and the lower curve respectively, and x the deflection.

Fig. 15 shows the relation between the coefficients in the Eq. (1) and the configuration of the loop. The coefficient A corresponds to the load at zero deflection and the coefficient B to the tangential slope of the curve at zero deflection. The area of the loop refers to the coefficients A and C, and the equivalent viscous damping factor is expressed in the Eq. (2). The backbone curve y_{BB} of the loop is expressed by the coefficients B and D as in the Eq. (3).

$$h_{eq} = \frac{1}{2\pi}\frac{8}{15}(6A + C) \quad (2) \qquad y_{BB} = B(x - x^5) + D(x^3 - x^5) + x^5 \quad (3)$$

These coefficients were obtained by the least squares method applied to the experimental results. The simulated curves, shown in Fig. 16 as an example, are in good agreement with those from the experiments.

MODEL BY PIECE-WISE-LINEAR SYSTEM It may be more convenient and effective in the response analyses to use the load-deflection relation expressed by the combination of the linear segments than that by the polynomial expression. Fig. 17 shows an example of the simulated loop described in the following. The experimental curve was simulated by six linear segments joining the peaks and the positions where the curve had the maximum curvature. Many experimental curves were applied to the above linear system model, and some effective properties on it were obtained. The slope k_1 was about 1.5 ~ 2.0 times of the equivalent rigidity k_{eq} defined as the slope of line going through the origin and the peak. The slope k_2 was about 0.3 ~ 0.5 times of k_{eq}. The break occured at the load of about 0.3 times of the maximum load... in both loading and unloading. And the loop was symmetrical about the origin of the co-ordinate if the deflection was constant under the load reversals.

6 CONCLUSIONS

From the results of the static cyclic loading tests on the reinforced concrete shear walls, the following conclusions can be drawn.

Initial shear cracks occur at the deflection of about 0.4×10^{-3} rad. Average shear stress at the cracking is about 12 ~ 17 kg/cm^2 in 0.25 % wall reinforcement ratio specimens and 19 ~ 26 kg/cm^2 in 0.5 %.

The strength of the specimen reaches to the maximum at the deflection of about 4×10^{-3} rad. Average shear stress at the ultimate strength is about 36 ~ 48 kg/cm^2 under the nonaxial load and 58 ~ 69 kg/cm^2 under the axial load.

Equivalemt rigidity reduces as the number of loading cycles increase and this tendency is more remarkable in the large deflection. The ratio of the equivalent rigidity of the 30th loading cycle to that of the first at the same deflection is about 60 ~ 85 %.

Equivalent viscous damping factor reduces to about 0.03 in the several loading reversals and after that it remains constant. This is independent of the deflection, the axial load and the wall reinforcement ratio.

Two idealized models are proposed for the steady state hysteresis loop of the reinforced concrete shear wall. The one is expressed in polynomial equations of 5th order. The other is composed of the linear segments defined by a simple rule.

ACKNOWLEDGEMENTS : The authors wish to thank Professor J.Ogawa, Tohoku University, for his kind advise. Messrs. M. Hoshi and A. Owada kindly assisted in this work. Financial supports of Tohoku Electric Power Co. is greatly appreciated.

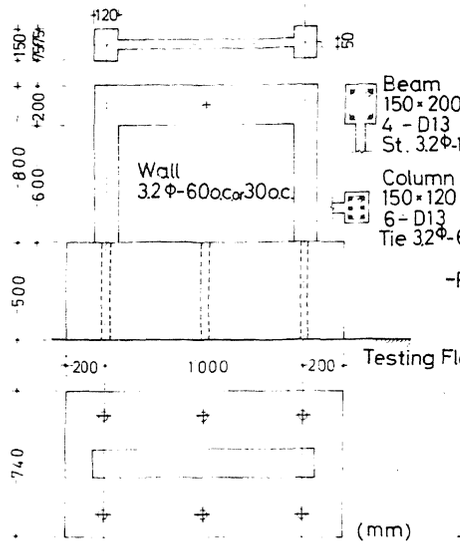


Fig. 1

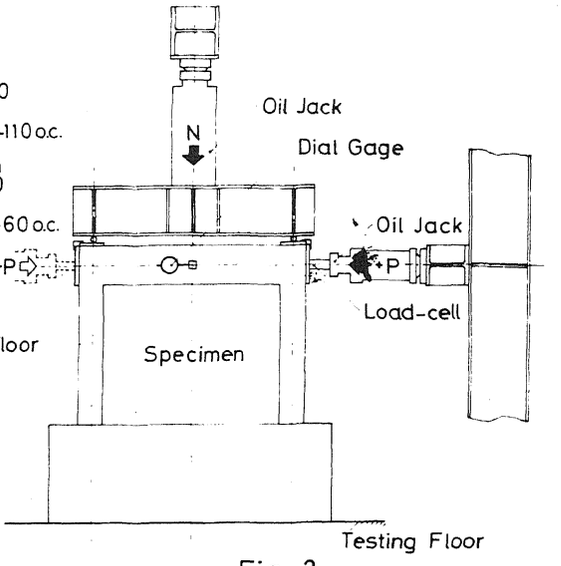
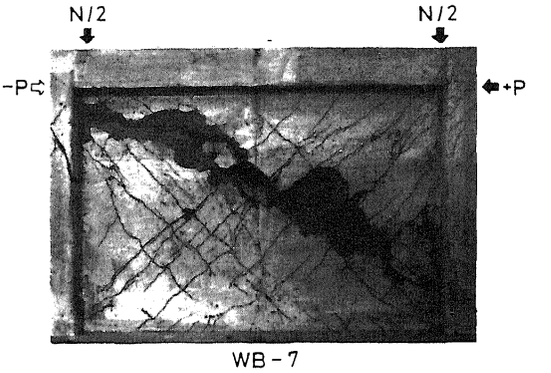


Fig. 2

Fig. 3



WB-7

Fig. 4

Table 1

Specimen No.	P_w	N	R (n)	Cracking P	Cracking τ	Cracking R	Ultimate P	Ultimate τ	Ultimate R
WB-1	0.25	0	4(30)→10(2)	6.8	13.7	0.57	17.7	35.7	4.00
2			2(30)→4(10)→10(10)	6.3	12.7	0.43	18.8	37.9	4.06
3			0.5(30)→2(10)→4(10)→10(2)	7.5	15.1	0.43	21.1	42.5	4.00
4			10(1)→20(one way)	5.7	11.5	0.36	23.1	46.6	7.14
5		20		8.4	16.9	0.53	34.1	68.8	7.14
6	0.50	0	same as WB-1	9.2	18.5	0.37	24.0	48.4	3.90
7		20		13.0	26.2	0.62	31.0	62.5	3.87
8		40		10.2	20.6	0.57	28.7	57.9	4.00

P_w : Wall Reinforcement (%)
N : Axial Load (t)
R : Translation Angle ($\times 10^{-3}$ rad.)
(n) : Number of Loading Cycles
P : Shearing Force (t)
$\tau = P/A_w$: Shearing Stress (kg/cm²)
A_w : Area of Shear Wall (cm²)

WB - 1

P_w = 0.25 %
N = 0 t
$P_{cr.}$ = 6.8 t (R = 0.57×10^{-3} rad.)
$P_{max.}$ = 17.7 t (R = 4.00×10^{-3} rad.)

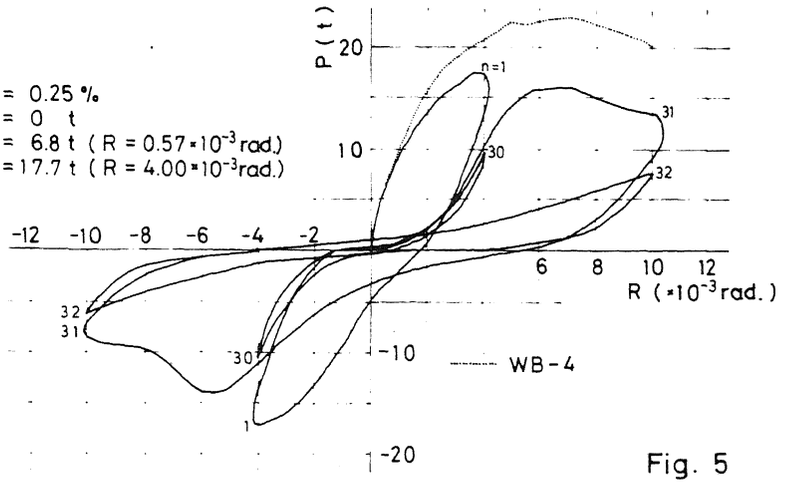


Fig. 5

WB - 2

P_w = 0.25 %
N = 0 t
P_{cr} = 6.3 t (R = 0.43×10^{-3} rad.)
P_{max} = 18.8 t (R = 4.06×10^{-3} rad.)

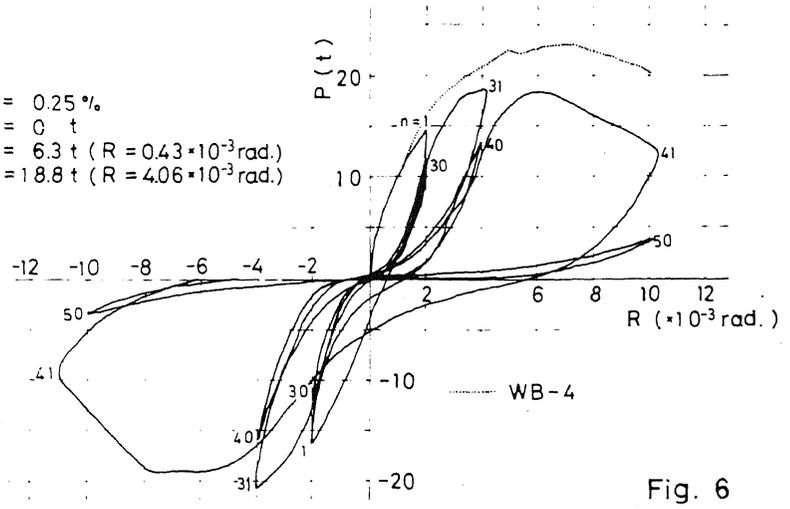


Fig. 6

WB - 3

P_w = 0.25 %
N = 0 t
$P_{cr.}$ = 7.5 t (R = 0.43×10^{-3} rad.)
$P_{max.}$ = 21.1 t (R = 4.00×10^{-3} rad.)

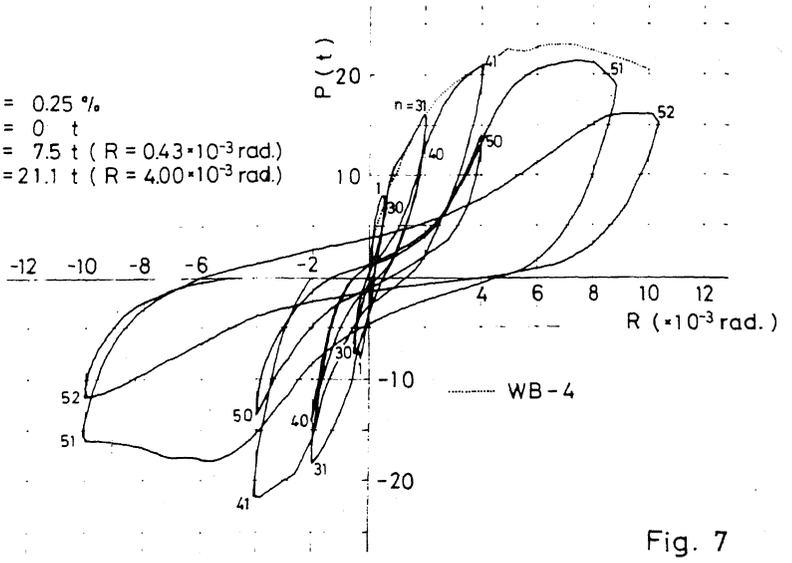


Fig. 7

WB - 6

P_w = 0.50 %
N = 0 t
$P_{cr.}$ = 9.2 t (R = 0.37 × 10^{-3} rad.)
$P_{max.}$ = 24.0 t (R = 3.90 × 10^{-3} rad.)

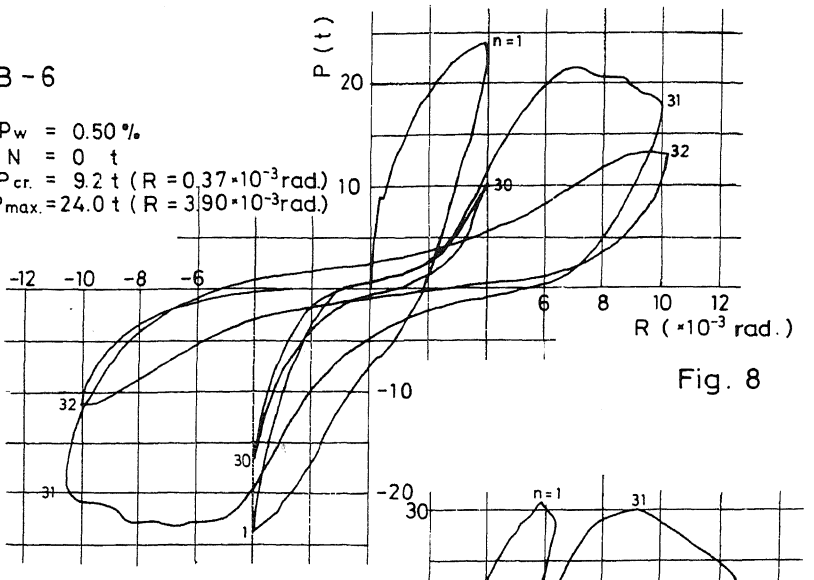


Fig. 8

WB - 7

P_w = 0.50 %
N = 20.0 t
$P_{cr.}$ = 13.0 t (R = 0.62 × 10^{-3} rad.)
$P_{max.}$ = 31.0 t (R = 3.87 × 10^{-3} rad.)

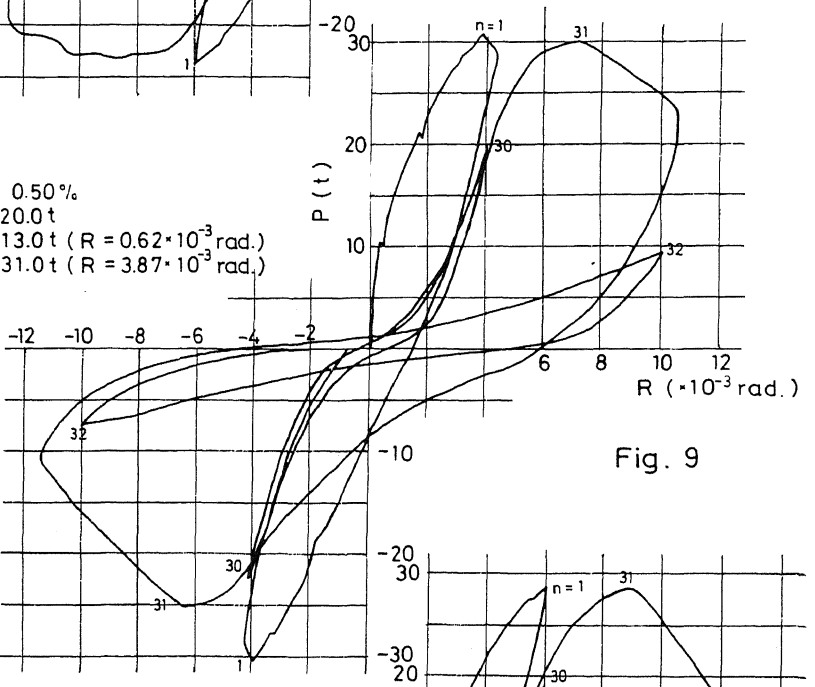


Fig. 9

WB - 8

P_w = 0.50 %
N = 40.0 t
$P_{cr.}$ = 10.2 t (R = 0.57 × 10^{-3} rad.)
$P_{max.}$ = 28.7 t (R = 4.00 × 10^{-3} rad.)

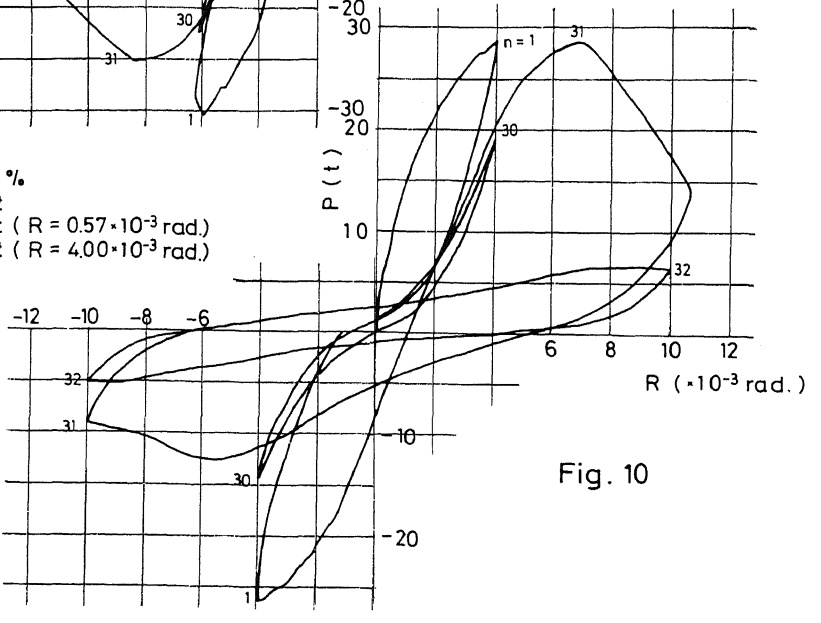
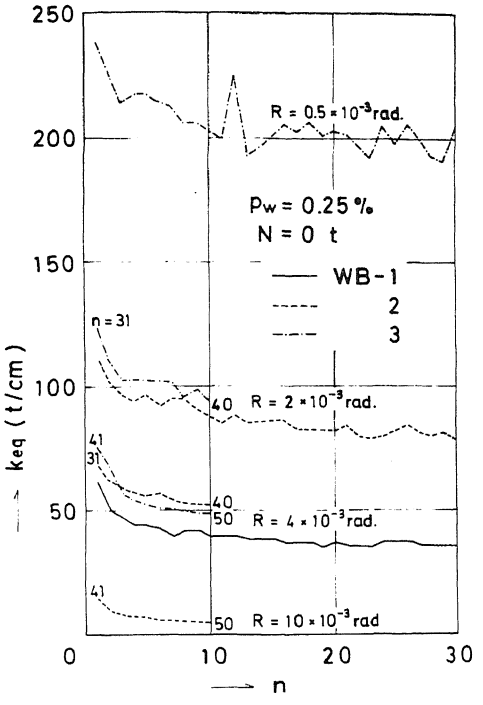


Fig. 10



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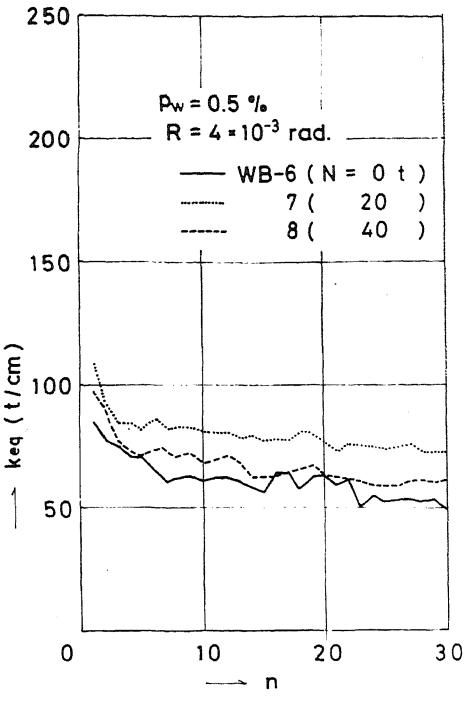

Fig. 12

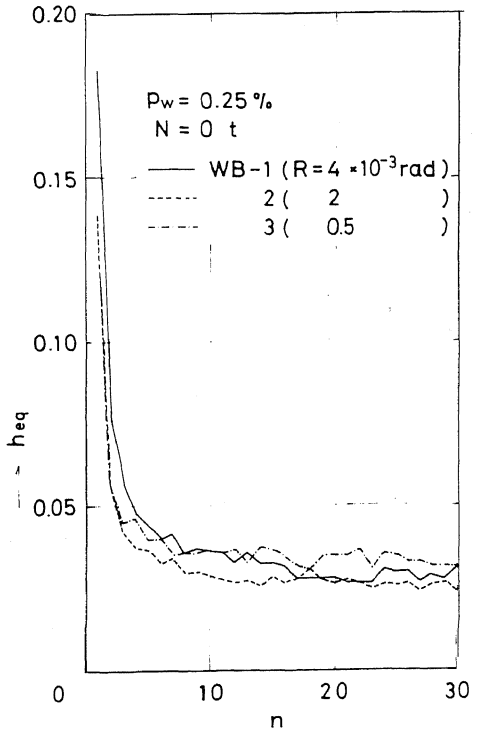

Fig. 13

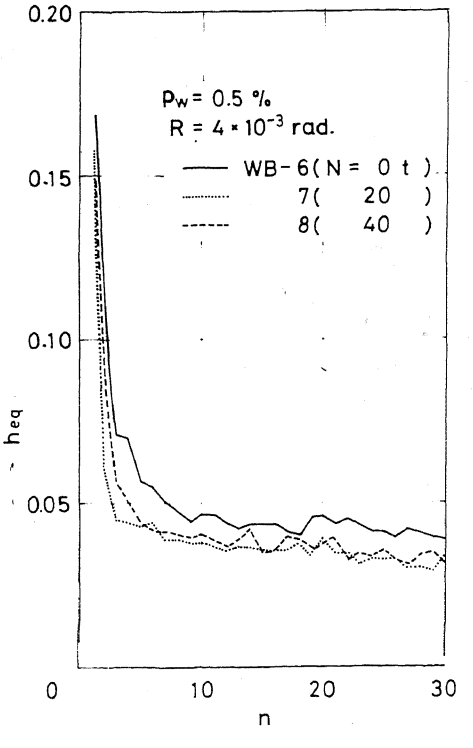

Fig. 14

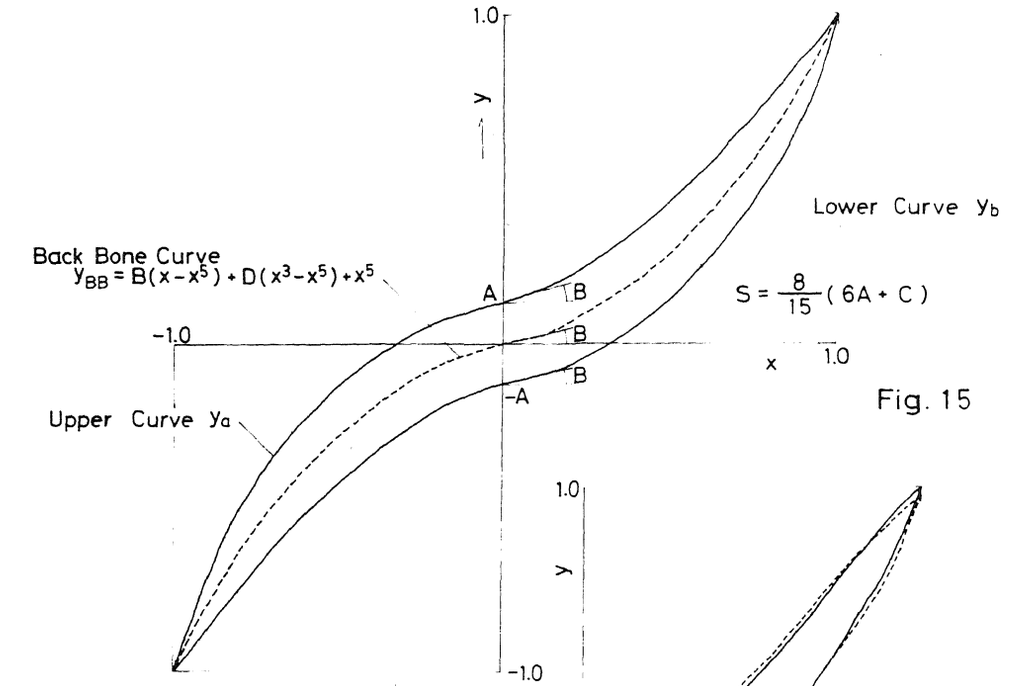

Fig. 15

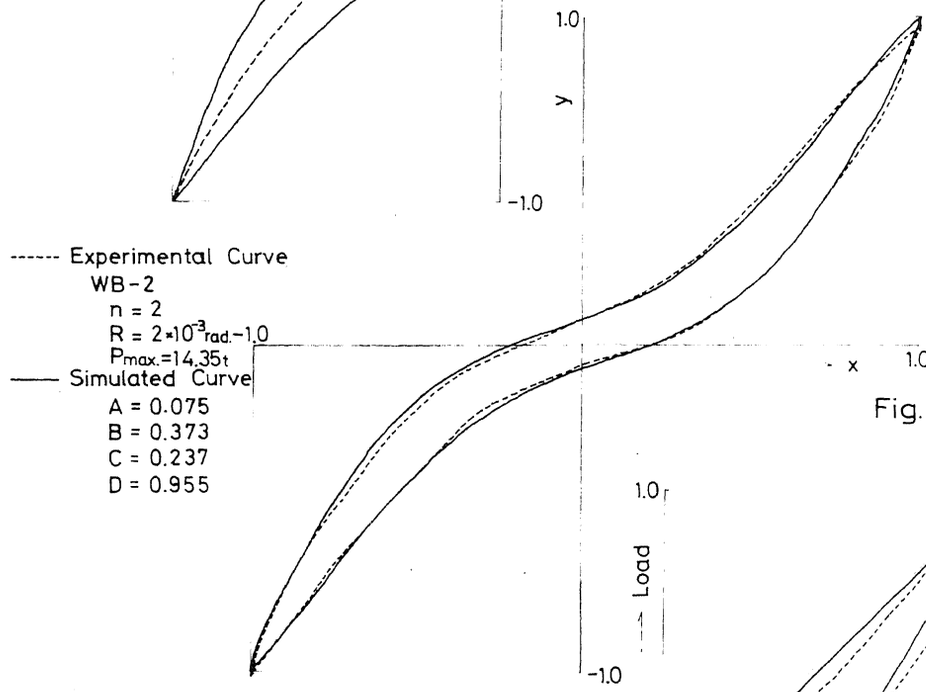

Fig. 16

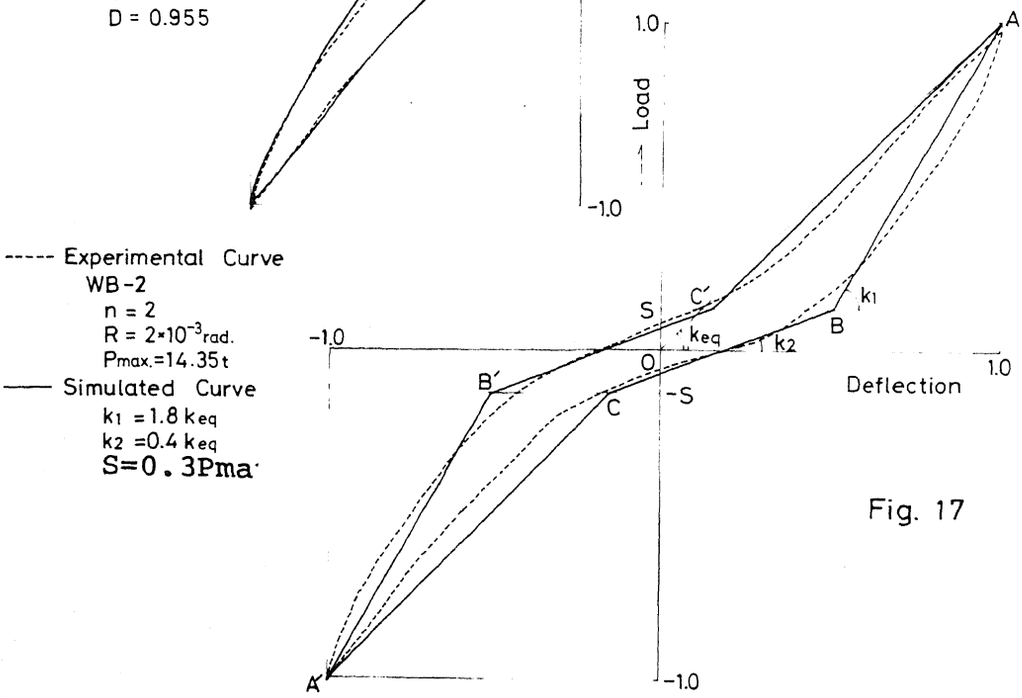

Fig. 17