

Cyclic loading tests of reinforced concrete column strengthened with steel tube

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ABSTRACT: As shear strengthening method of existing reinforced concrete column, which has collapse mechanism determined in shear rupture, the method by covering the original existing reinforced concrete column with additional "steel plate + filler" has been considered effective. However, method to evaluate its effectiveness quantitatively has not suggested at present, and it has not established as a design method. This paper describes the results of static loading test aiming to confirm the effectiveness of strengthening and to establish the evaluation method concerning the shear strengthening by "steel plate + filler" for existing reinforced concrete column. Moreover a practical example of applying this process to the seismic strengthening of an actual existing building is introduced.

1 INTRODUCTION

Existing reinforced concrete columns that has collapse mechanism determined in shear rupture are most effectively reinforced against shear by wrapping them with steel plate and filling the gap between the column and wrapping plate with mortar (see Tomii (1985)). However, specific design involving the thickness of the steel plate and the thickness of the mortar filling as parameters has not been sufficiently studied.

This paper presents the results of static loading tests carried out to confirm the effectiveness of the steel plate and filler method of strengthening existing reinforced concrete columns, and to obtain basic data for seismic strengthening design. A practical example of applying this process to the seismic strengthening of an actual existing building is introduced.

2 EXPERIMENTAL METHOD

2.1 Test specimens

5 specimens were used: 1 column that has collapse mechanism determined in shear rupture as the basic specimen and 4 columns strengthened by the steel plate plus filler method (see Table 1). The shape, dimensions, and reinforcing bar arrangement details of the basic specimen, and the details of the strengthened specimens are shown in Fig. 1. Scale factor of these specimens are about

1/3. The flexural strength of the reinforced concrete column part was about twice the shear strength. The main reinforcement ratio of the column, ρ_g , was set at 5%.

The shear strength parameters are the thickness of the steel plate and the width of the gap between the column and the plate (i.e., the thickness of the filler). Two thicknesses of steel plate were used; considering that, for the case of shear strengthening, the upper limit of the shear reinforcing bar ratio that exhibits the shear reinforcement effect is 1.2% (see A.I.J.(1988)), the steel plate thicknesses of 1.6 mm, which corresponds to a hoop reinforcement ratio, ρ_w , of 1.1% to 1.2%, and twice that thickness, t_1 , 3.2 mm, were selected. For the filler thickness, t_2 , the two values of 10 mm and 25 mm were selected, considering practicality in actual strengthening work and the minimum filler thickness required when constructing the test specimens. The reinforcing plate is thin steel plate formed into U-shapes that are placed around the reinforced concrete column and welded together to form a box-shape that encloses the column. So that no axial force is applied to the steel plate, a 10-mm clearance is left at both ends of the column, between the plate and the base beam and between the plate and the upper beam.

The reinforced concrete column test specimens are constructed by first assembling the mold in a horizontal position. Then, after arrangement of reinforcing bars, concrete that has a specified concrete strength of

1600 N/cm², water-cement ratio of 66% and slump of 17-cm is poured. The strengthening with steel plate is done after the mold is removed and the specimen has been stood up. After the column has been covered with the plate, the filler (pre-mixed, non-shrinking, high-strength mortar) is pressed into the gap between the column and plate.

The physical properties of the concrete, filler, reinforcing bar, and steel plate used in this test are listed in Table 2 and Table 3.

2.2 Loading method

The loading apparatus is depicted in Fig. 2. The specimen column is fixed to the test floor slab with a fixed equipment and high tensile strength bolts (42φ, SCM435). The upper end of the specimen column is firmly attached with high tensile strength bolts (42φ) to the L-shaped beam of the loading apparatus.

The horizontal load on the test specimen is applied via the L-shaped beam by a 750-kN capacity actuator fixed to the wall of the apparatus. The vertical load is applied by a 300-kN capacity actuator installed on the reaction beam of the apparatus. A 500-kN capacity roller bearing is placed between the frame and the actuator to follow the horizontal displacement of the specimen.

Force is applied in the horizontal direction with gradually increasing displacement according to the loading process shown in Fig. 3. A constant vertical load is applied, including the weight of the loading apparatus, to produce an axial stress intensity of $\sigma_0 = 0.25 F_c = 450 \text{ N/cm}^2$ (axial force = 281.25 kN).

2.3 Measurement method

As for the configuration of the force measurement system, the data for the horizontal and vertical loads is acquired by shear load cells attached to the front end of the actuators. That data, together with jack-stroke data, is sent directly from the actuator control computer via an interface to the measurement control computer.

The displacement of each part of the test specimen is measured by displacement transducers with a capacity 50mm or 25mm placed in measurement frames fixed to the surface of the base beam. Also, to clarify the specimen failure mode, the strain in the axial direction at the top and base of the column's main bar which causes the maximum bending moment is measured with a one-axis strain gage (5-mm detection length). For the strengthened specimen, strain at the main points of the steel plate are measured with three-axis strain gages (5-mm detection length). The strain measurement positions

are shown in Fig. 1.

The displacement and strain data is obtained with digital strain measurement equipment and recorded through on-line control by computer.

3 EXPERIMENT RESULTS

3.1 Cracking pattern and failure mode

The cracking pattern of each specimen is shown in Fig. 4. Here, for the strengthened specimens, the steel plate and filler are removed after the test, and the cracking in the reinforced concrete column part is observed.

3.1.1 Basic test specimen (before strengthening): C-00

The initial cracking appears in the second loading cycle as a flexible crack on the tension side at the top of the column at a load of 84 kN (rotation angle of member $R = 1/800$). As the load is increased, new flexible cracks appear at the head and foot of the column, and these flexible cracks steadily extend further in the 45° direction and take on the appearance of flexible shear cracks. Shear cracks appear near the top of the column in the third cycle at a load of 105 kN ($R = 1/430$). In the eighth cycle at the time of maximum deformation ($R = 1/200$), the ultimate strength of 120.3 kN is reached, and in the following cycles the shear cracks at the top and base of the column extend and vertical cracks (bond splitting cracks) appear along the main reinforcing bars of the column.

3.1.2 Strengthened specimens: C-11, C-12, C-21, C-22

In the strengthened specimens, flexible cracks appear at the boundary between the column and the top and base beams as $R = 1/500$ is approached; beginning at from about $R = 1/200$ to $R = 1/100$, a tendency for the crack width to increase is confirmed. For the concrete part strengthened with steel plate, after the loading test is finished, stopped when slight shear cracking near the top and base of the column could be confirmed.

For specimens C-12 and C-22, which have 3.2-mm thick steel plate, concentration of the shear cracking at the top and base of the column is seen regardless of the mortar filler thickness. However, for specimen C-11, with the steel plate thickness of 1.0 mm and the thinner mortar filling, in addition to the shear cracking at the top and base of the column, bond splitting cracking along the main reinforcing bars of the column extends to the central part of the column and the amount of cracking is relatively large; in contrast, for specimen C-21, which

has the thick mortar filling, the amount of cracking is much smaller than for the other three specimens, beginning with C-12, and the bond splitting cracking along the main reinforcing bars of the column is not seen at all. No compression failure of the concrete occurs in any of the specimens.

3.2 Ultimate strength

The ratio of the ultimate strength and the rotation angle of member at the ultimate strength, and the calculated bending strengths and shear strengths of the specimens are compared in Table 4. Here, the bending strength of each specimen is calculated from Eq. (1) and the shear strength of the unstrengthened specimen is calculated from Eq. (2).

1) Bending strength: Q_{mu} (unit: N)

$$Q_{mu} = 2 \cdot [0.8at\sigma_y D + 0.5N_0 D (1 - \frac{N_0}{BD\sigma_c})] / H \quad (1)$$

Here, a is the cross-sectional area of the tension reinforcement (cm^2). σ_y is yield strength of tension reinforcement (N/cm^2). D is depth of column (cm). B is width of column (cm). N_0 is axial force of column (N). σ_c is concrete compressive strength (N/cm^2).

2) Shear strength: Q_{su} (unit: N)

$$Q_{su} = [\frac{0.068pt^{0.23}(\sigma_c + 1800)}{M/Qd + 0.12} + 2.7\sqrt{p_w \cdot 10\sigma_w}] B \cdot j \quad (2)$$

Here, pt is the tension reinforcement ratio (%), where $pt = at / (Bd) \times 100$. M/Qd is shear span ratio. d is effective depth (cm). p_w is the ratio of hoop reinforcement. σ_w is yield strength of hoop reinforcement (N/cm^2). σ_o is axial stress (N/cm^2). j is lever arm of the internal couple ($= d \cdot 7/8$) (cm).

The ultimate strength of the unstrengthened specimen is nearly the same as the calculated shear strength value, and is nearly 50% of the calculated bending strength. In contrast to this, the calculated bending strength of the strengthened specimens is nearly the same, or at most, 20% higher, and a reinforcement effect of from 1.8 to 2.2 times higher than the unstrengthened specimens is seen. However, the relationship between steel plate and mortar filler thickness and the ultimate strength is beyond the scope of the present experiment and has not been clarified.

3.3 Restoring force characteristics

3.3.1 Load-deformation curve

The load-deformation curves and their positive-side envelope curves are shown in Fig. 5 for each of the specimens. The rigidity of the unstrengthened specimen

begins to decrease at loads of about 50 kN, and the appearance of shear cracking (at a load of 105 kN) is accompanied by a sharp increase in deformation. For positive direction loading, nearly ultimate strength is reached at $R = 1/300$, and is maintained until about $1/200$. After that, there is a gradual reduction in strength. In contrast with this, negative-direction strength reaches the ultimate strength at $R = 1/300$, and then the strength gradually decreases. Also, the strength at maximum deformation ($R = 1/52$) is about 60% of the ultimate strength.

The initial rigidity of the strengthened specimen is much higher than that of the unstrengthened specimen, exhibiting the effect of the steel plate and mortar filling. However, at loads of around 20 to 40 kN, a drop in rigidity occurs, and afterwards, the rigidity is practically the same as that of the unstrengthened specimen.

There is no remarkable difference in restoring force characteristics due to differences in steel plate thickness and filling thickness up to $R = 1/200$ to $1/150$; in the region of large displacement after that, some difference is observable. That is, for specimens C-12, C-21, and C-22, which have either thick plate or thick filler, or both thick plate and thick filler, the main reinforcing bars of the column yield at $R = 1/100$, and after that the strength increases because of the influence of effects such as the increase in compression strength on the concrete due to strain hardening of the reinforcing bars and the constraining effect of the steel plate. In contrast with this, for specimen C-11, in which the steel plate and mortar filling are both thin, the constraining effect of the plate is less than in the other specimens, and the main reinforcing bars finally reach the yielding point at $R = 1/55$. The strength at this yielding time is about the same as for the other samples.

3.3.2 Hysteresis and equivalent viscous damping factor

The non-dimensional loops of the load-deflection curves for specimens C-00 and C-11 are shown in Fig. 6. The horizontal axis of these graphs (displacement) is normalized by the absolute maximum displacement of each positive-negative cycle; the vertical axis (load) is normalized by the absolute maximum load of each positive-negative cycle. Also, the calculated hysteresis area and equivalent viscous damping factor of each cycle loop are listed in Table 5.

The shape of the non-dimensional loop for the unstrengthened specimen (C-00) is spindle-shaped up to $R = 1/200$, but beyond $R = 1/150$, where there is a drop in strength, the loop takes on a reverse S shape. The equivalent viscous damping factor calculated

from the hysteresis area is about 8% to 10% for the 1st cycle and 7% to 8% for the 2nd cycle and the following cycle, and is quite unrelated to the rotation angle of member, R. The shape of the non-dimensional loop for the strengthened specimen differs from that of the unstrengthened specimen; it is spindle-shaped up to $R = 1/125$, and at $R = 100$ there is a slight tendency for a reverse S shape to appear. Particularly, up to $R = 500$ the loop is a larger spindle shape than for the unstrengthened specimen.

Also, for $R = 1/500$ or less, the equivalent viscous damping factor is larger than for the unstrengthened specimen: 11% to 15% for the 1st loop and 9% to 12% for the repeated loop at $R = 1/500$. However, for the loops at $R = 1/300$ and above, the values are 6.5% to 11.5% for the 1st loop and 5.5% to 9.5% for the repeated loop, and although there is dispersion in the data for specimens, the values are practically the same as for the unstrengthened specimen. Specimen C-22, in which the steel plate and mortar filler are both thick, has a larger equivalent viscous damping factor than the other strengthened specimens, and it was found to have superior energy absorption ability.

3.4 Steel plate strain

The relationship between load and strain in the steel plate orthogonal to the axis of member in the vicinity of the shear cracking of the strengthened specimens is shown in Fig. 7. The strain properties of the steel plate at the base of the column exhibit a complex hysteresis in the early stages of relatively light loads, but after bond splitting with the filling mortar is lost, a similar hysteresis with the shear reinforcing bars is exhibited, and residual strain due to repeated force applications accumulates. The degree of strain for the same horizontal load decreases in inverse proportion to the plate thickness, and the stress operating on the plate takes on a virtually constant proportion, unrelated to the plate thickness.

The distribution of the main strain on the steel plate at ultimate strength is shown in Fig. 8. From this distribution, we can see that the principal strain properties of the steel plate at the time of large deformation, are nearly pure shear strain in the central part of the column, and nearly shear reinforcing bar type simple tension strain at the top and base of the column.

The shear stress of the steel plate calculated on the basis of the test results is shown in Table 6. Here, σ_u is the value of the difference between the ultimate strength of the strengthened column with steel plate and the unstrengthened column (C-00). σ_{eq} is the equivalent shear stress calculated on

the basis of the strain in the column base part of the steel plate (orthogonal to the member axis) at the time of ultimate strength. These two results agree well, and it is seen that the steel plate very effectively bears the shear stress in place of the shear reinforcing bars.

4 EXAMPLE OF SEISMIC STRENGTHENING OF THE EXISTING BUILDING BY STEEL PLATE WRAPPING

An example of seismic strengthening for the existing NTT's building by wrapping first-floor columns with steel plate is shown in Photograph 1. Comparison of seismic capacity before and after strengthening shows that the unified seismic performance index (I_s), which is guideline for evaluation of seismic capacity of existing reinforced concrete buildings established by the Japan Building Disaster Prevention Association, improved from 0.28 to 0.46.

5 CONCLUSION

It has been shown that steel plate and filler strengthening of existing reinforced concrete columns that has collapse mechanism determined in shear rupture can check the shear failure process and transfer it to a flexural ultimate mode that has a large deformation capacity. At that time, it is possible to evaluate the flexural ultimate strength of the column that has been strengthened with steel plate and filler from the flexural strength of the unstrengthened concrete column. The relationships between the thicknesses of the steel plate and filler and the strengthening effect are beyond the scope of the present experiment and have not been clearly explained. No reinforcement effect was obtained by simply making the thicknesses of the plate and filler large, but with regard to the steel plate, in order to maintain external surface rigidity at the time the filler is injected and to halt the local failure of the concrete at times of large distortion, it is probably necessary to maintain the plate thickness at about the levels used in this experiment.

REFERENCE

- Tomii, M. et al. 1985. Experimental studies on the design method to prevent the shear failure of reinforced concrete short columns by using steel tube (in Japanese). Summaries of technical papers of annual meeting architectural institute of Japan structure II: 413-420
- A.I.J. 1988. Standard for structural calculation of reinforced concrete structures

Table 1. List of specimens

	B × D (cm)	column			steel plate		mortar	
		main bar	hoop		t ₁	2·t ₁	t ₂	2·t ₂
		a _c (cm ²) ρ _c (%)	a _s (cm ²) ρ _s (%)	a _w (cm ²) ρ _w (%)	(mm)	B	(mm)	B
C-00								
C-11	25cm × 25cm A _c = 625cm ²	31.84	9.95	0.25	1.6	0.0128	10	0.08
C-12		5.09	1.59	0.10	1.6	0.0128	25	0.20
C-21	100cm	(16-D16)	(5-D16)	2-4φ @100	3.2	0.0256	10	0.08
C-22	M/Qd=2.27				3.2	0.0256	25	0.20

R: rotation angle of member

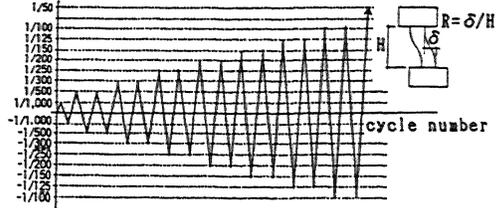


Figure 3. Cyclic loading process

positive force ← negative force

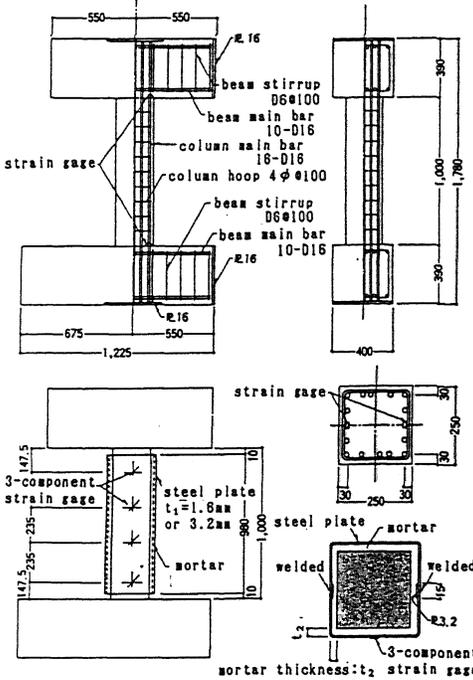


Figure 1. Detail of specimens

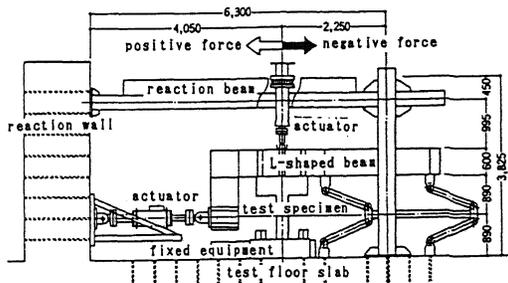


Figure 2. Test setup

Table 2. Physical properties of concrete and mortar

	specified concrete strength (N/cm ²)	concrete			mortar compressive strength (N/cm ²)
		compressive strength (N/cm ²)	elastic modulus × 10 ⁴ (N/cm ²)	ultimate strain (× 10 ⁻⁴)	
C-00	1800	2780	2.10	2446	189
C-11		2780	2.24	2389	189
C-12		2900	2.25	2380	233
C-21		2830	2.17	2491	198
C-22		2850	2.22	2554	132

Table 3. Physical properties of reinforcing bars and steelplate

	diameter & thickness (mm)	yield strength (kN/cm ²)	ultimate strength (kN/cm ²)	elongation (%)
column main bar	D16(SD345)	—	59.6	3.41
hoop	4φ (SWN-B)	39.6	60.0	19.7
steel	1.6mm(SS400)	29.1	39.0	43.7
plate	3.2mm(SS400)	28.5	43.2	39.2

negative force ← → positive force

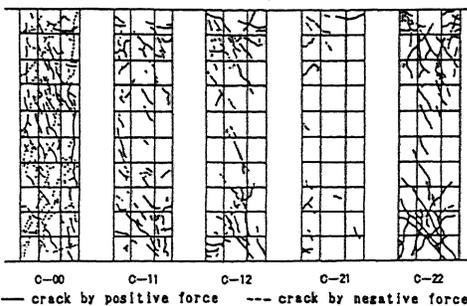


Figure 4. Crack pattern

Table 4. Test results of ultimate strength and rotation angle of member:R

		ultimate strength		bending strength		shear strength	
		Q _u (kN)	R	Q _{bu} (kN)	Q _u /Q _{bu}	Q _{su} (kN)	Q _u /Q _{su}
C-00	+	120.3	1/205	218.5	0.56	126.8	0.95
	-	115.3	1/304	216.5	0.53	126.8	0.91
C-11	+	215.2	1/65	216.5	0.99	—	—
C-12	+	267.2	1/49	217.1	1.23	—	—
C-21	+	255.8	1/52	215.9	1.18	—	—
C-22	+	248.2	1/47	216.8	1.14	—	—

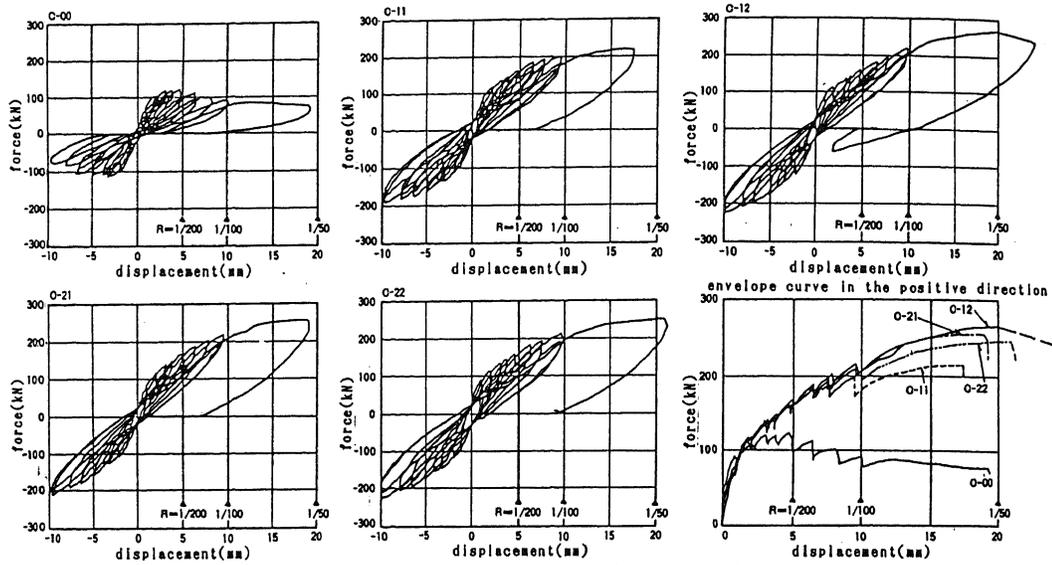


Figure 5. Load-deflection curves and envelope curve in the positive direction

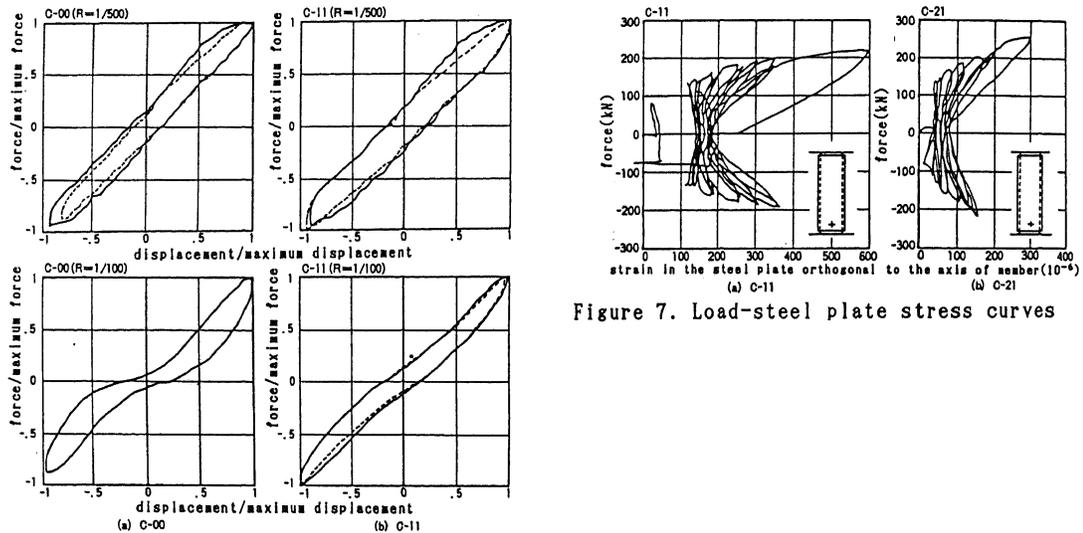


Figure 7. Load-steel plate stress curves

Figure 6. Normalized load-deflection curves

Table 5. Hysteresis area and equivalent viscous damping factor

	1/1000	R=1/500		R=1/300		R=1/250		R=1/200		R=1/150		R=1/125		R=1/100	
	1st	1st	2nd	1st	2nd										
C-00	4.81 (10.9)	12.7 (9.78)	10.7 (7.92)	21.3 (8.98)	18.0 (7.74)	22.4 (8.16)	18.9 (7.17)	33.4 (9.36)	22.9 (7.38)	36.9 (8.25)	27.9 (7.23)	48.7 (10.3)		50.2 (9.63)	
C-11	7.79 (14.5)	17.9 (12.3)	13.9 (9.73)	25.4 (9.29)	21.1 (7.69)	25.7 (7.68)	22.3 (6.76)	34.5 (7.10)	30.6 (6.30)	53.6 (7.45)	45.7 (6.51)	60.9 (6.72)	54.0 (6.34)	91.9 (7.76)	74.5 (6.88)
C-12	8.88 (16.1)	19.3 (12.3)	15.2 (10.4)	27.0 (9.14)	19.1 (7.22)	26.7 (7.08)	23.0 (6.54)	36.6 (7.03)	30.2 (6.31)	59.4 (7.61)	48.0 (6.46)	65.6 (6.68)	59.8 (6.49)	104.0 (7.65)	88.2 (6.84)
C-21	7.29 (14.0)	17.7 (11.4)	12.5 (9.05)	24.8 (8.88)	19.0 (6.91)	24.2 (6.79)	20.8 (6.15)	33.1 (6.54)	28.6 (5.78)	48.4 (6.54)	38.7 (5.52)	62.4 (6.48)	49.4 (5.41)	88.5 (6.75)	73.5 (5.87)
C-22	12.8 (19.7)	22.9 (14.6)	16.5 (12.2)	33.6 (11.4)	24.7 (9.56)	34.2 (9.03)	29.3 (8.24)	43.3 (8.39)	37.1 (7.62)	64.5 (8.39)	52.2 (7.35)	74.4 (7.64)	64.4 (7.04)	119.0 (8.63)	96.6 (7.79)

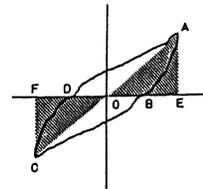
the upper row:hysteresis area(kN·cm)

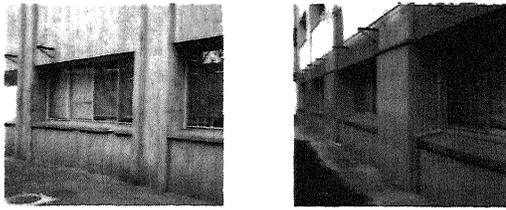
1st:1st cycle

the lower row:equivalent viscous damping factor(X)

2nd:second cycle or the following cycle

calculation method of
equivalent viscous
damping factor
$$\eta = \frac{1}{2\pi} \frac{\text{area}(ABCD)}{\text{area}(\triangle OAE + \triangle OCF)}$$





before after
Photograph 1. Example of strengthening

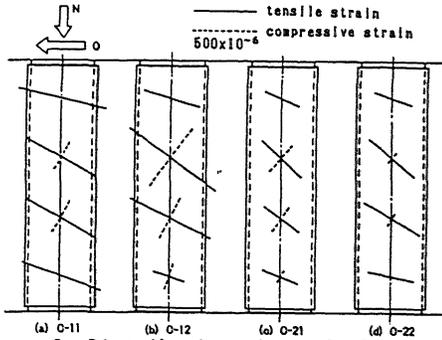


Figure 8. Distribution of steel plate stress at maximum load

Table 6. Shear force of steel plate

	ultimate strength		shear strength		calculated strain of steel plate near the base of column			
	Q_u (kN)	τ_u (N/cm ²)	cQ_u (kN)	$c\tau_u$ (N/cm ²)	$s\tau_u$ (N/cm ²)	$s\epsilon_x$ ($\times 10^{-6}$)	$s\epsilon_x$ (N/cm ²)	
C-11	215.2	344	120.3	192	152	700	15	
C-12	287.2	428			238	900	19	240
C-21	255.8	409			217	400	8.4	220
C-22	248.2	397			205	400	8.4	220

Q_u : ultimate strength of strengthened specimens (C-11, C-12, C-21, C-22) $c\tau_u = cQ_u/BD$
 cQ_u : ultimate strength of unstrengthened specimens (C-00) $\tau_u = Q_u/BD$
 $s\tau_u = c\tau_u$ $s\epsilon_x$: ultimate strain $s\tau_u = E \cdot s\epsilon_x$ $s\epsilon_x = \tau_u \cdot 21.7/E$