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Study on Structural Performance of Reinforced Concrete Columns with Waist-High Walls Strengthened by Carbon Fiber Reinforced Plastic Sheets

by H. Nagai, T. Kanakubo, Y. Jinno, Y. Matsuzaki, and S. Morita

Synopsis:

This research aims on understanding the influence of the strengthening method using carbon fiber reinforced plastic (CFRP) sheets on the performance of 13 reinforced concrete columns with waist-high walls. Main parameters of the specimens include the thickness and height of the attached walls, axial load, and the amount of CFRP sheets. The strengthening method is done by wrapping the upper portion of the column with sheets in a closed form. Also, the waist-high walls are equipped with holes where the carbon fiber strands (CF-anchor) are inserted and anchored to the ends of the sheets attached only on the surface of the lower portion of the column. Test result show that there is a great improvement in the ductility of the shear-failure type specimens when strengthened with CFRP. Also with an increase in the amount of the sheets, the ductility is further enhanced. The specimens strengthened using CFRP with CF-anchor also show higher ductility than the specimen where only the upper column is strengthened. The bending and shear strengths of the columns with waist-high walls can be calculated by using effective column height h_e considering the presence of the wall portions.

Keywords: carbon fiber; column; plastic; reinforced concrete

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INTRODUCTION

The South Hyogo Earthquake, which occurred at January 17, 1995 in Japan, damaged a quite large number of structures, such as buildings, wooden houses, bridges, offshore constructions, and so on. The epicenter was positioned near to the city of Kobe, which is one of the oldest cities in Japan. A maximum acceleration of over 800 gal was observed at JMA Kobe. A huge number of old buildings are still existing throughout Japan. If an earthquake with the same magnitude as the last one occur in another city, a lot of buildings will be destroyed. It is essential to strengthen or upgrade old buildings.

Two methods for strengthening or upgrading buildings are popular in Japan. One is by increasing the sectional area by post-casting concrete, and the other is by confining members by steel plates. These methods, however, need many processes, much time, good techniques and heavy machines. Recently, a strengthening method using continuous fiber, such as carbon, glass and aramid has been the main focus because of its simplicity in construction and economy. The simplest way to use the fiber for strengthening is to wrap the members by sheets. Many investigations and studies concerning fiber sheet strengthening are now going on for both building and civil engineering structures in Japan. However, the effect of strengthening and the structural performance of the sheet reinforcement are still unclear at present. Also, previous studies dealt mostly on the square column and only a very few on columns with side walls which are used in actual building construction.

TEST PROGRAMS

Specimens

Thirteen reinforced concrete columns with waist-high walls are tested. The list of specimens and their dimensions are shown in Table 1 and Fig. 1, respectively. The following are the common specifications of the specimens. The column cross section is 300×300 mm and the specified concrete compressive strength is 24 MPa. The column bars used are 4-D13 (only No.6-2 used 4-ϕ13) and D6, for the main and lateral reinforcement, respectively, while the vertical and horizontal bars in the walls are 2-D4@80. The ratio of lateral reinforcement, p_w, is 0.13% and the ratio of horizontal wall bars, p_{sh}, is 0.17%. Also the clear span length is 900 mm, and the shear span ratio is 1.5.

Two types of carbon fiber sheets are used for strengthening the specimens, the $150g/m^2$ and $300g/m^2$ types, in terms of weight per unit area. Strength and elastic modulus is 4500MPa, 4170 MPa and 273GPa, 257 GPa, respectively. The strengthening method is done by wrapping the upper portion of the column with sheets in a closed form. Also, the waist-high walls are equipped with holes where the carbon fiber strands (CF-anchor) are inserted and anchored to the ends of the sheets attached only on the surface of the lower portion of the column. Method of reinforcing is shown in Fig. 2. Main parameters of the specimens include the thickness and height of the attached walls, axial load, amount of CFRP sheets, wall position (center side or eccentric side of column) and main bar type (deformed or round bar).

Mechanical properties of concrete, the reinforcement, carbon fiber sheet, and a photo of the CF-anchor are shown in Table 2, 3, 4 and Photo 3, respectively.

Cyclic loading is provided for all specimens using the antisymmetrical loading system shown in Fig. 3. The loading is carried out by controlling the drift angle (R). The loading history applied to all specimens is $R = \pm 1/400, \pm 1/200$ radians once, $R = \pm 1/100, \pm 1/67, \pm 1/50, \pm 1/33$ radians twice and $R = \pm 1/20, +1/15$ radians once. The shear force, relative displacement between the upper and the lower stubs and the strains of the reinforcements, CFRP sheet and CF-anchor are measured.

TEST RESULTS

Failure Progress

The progress of the experiment until the loading cycle to $R = 1/400$ radians was almost the same for all strengthening specimens. First, shear cracks commenced on the waist-high walls on both sides. Next, bending cracks occurred at the both ends of columns and extended as the displacement increased.

For specimens No.1-0, No.2-0, No.3-0, and No.5-0 shear cracks were observed on the upper columns extending toward both compression edges. At the loading cycle to $R = 1/395$ radians, the maximum load was attained and a drop in the shear force capacity was observed for the succeeding cycles. These specimens showed brittle behavior and that the yielding of main bars were not observed. This failure type is defined as diagonal tension failure (DT).

For other specimens, yielding of main bars (F) occurred at the loading cycle of $R = 1/100$ radians. For these specimens strengthened by CFRP sheets with CF-anchor (No.1-1, 1-2, 1-3, 2-2, 3-2, 4-2 and 5-2), a rupture of sheet (SR) after the yielding of main bars was observed coupled with a remarkable decrement in the shear force capacity. For specimens No.1-C2, where only the upper column is strengthened, shear failure (S) at the lower column portion adjacent to the waist-high walls was observed after yielding of the main bars. For specimens No.6-2, whose main bars are round steel bars, bond failure (BO) was observed. Photographs of representative specimens after loading are shown in Photo 4.

Comparison of Shear Force—Drift Angle Skeleton Curves

Shear force versus drift angle skeleton curves of specimens are shown in Fig. 5. For specimens not strengthened by CFRP sheets (No.1-0, No.2-0, No.3-0, No.5-0), the toughness of the column decrease as the thickness height and eccentric position are increased. For specimens strengthened with CFRP sheets (No.1-1, No.1-2, No.1-3), maximum loads attained are greater compared with specimen No.1-0 by about 25%. And the ductility is greatly improved, as the amount of CFRP sheet is increased. The following described the influence of the size of the wall, strengthened range, axial force and shape of main bars, on the ductility of the column basing from the results of specimen No.1-2. For the specimens with a greater wall thickness (No.2-2) and greater wall height (No.3-2), it was observed that the maximum loads attained are almost identical. However, there was a decreased in the ductility of the column. On the other hand, for the specimen having a wall at an eccentric position (No.5-2), the ductility of the column increased compared to specimen No.1-2. This reason for such is that there is an increase in the length of the shear span the wall is positioned eccentrically compared when it is positioned at the center. For specimen where in only the upper column is strengthened (No.1-C2), both the maximum load and the ductility decrease as compared with specimen No.1-2. Moreover for specimen loaded with a higher axial force (No.4-2), an increase in the maximum load attained and a decrease in the ductility are observed. Lastly, for the specimen using round main bars (No.6-2), there was a decrease in the maximum load but an increase in the deformation capacity compared with specimen No.1-2. This is mainly because the bond strength of the round steel bars with the concrete is weak compared to deformed bars.

DISCUSSION

Strengths Evaluation

Following formulas are used to calculate bending and shear strengths.

$$_cQ_{mu} = 2M_c / H$$

$$M_c = 0.5a_g \cdot \sigma_y \cdot g_1 \cdot D + 0.5N \cdot D\left(1 - \frac{N}{b \cdot D \cdot \sigma_B}\right) \quad (1)$$

$$g_1 = d_1 / D$$

$_cQ_{mu}$: calculated bending strength

M_c : bending moment of the independent column

a_g : total sectional area of the main bars

σ_y : yield strength of the main bars

d_1 : distance between centers of tensile and compressive main bars

N : axial force

D : column depth

b : column width

H : column length to evaluate the effect of waist-high walls

h_c, h_e, h is defined as follows

h_c : column length of independent column

h_e : effective height (1)

$$\frac{h_e}{h} = 1 - k\left(1 - \frac{h_c}{h}\right)\sqrt{\frac{t}{b}}\left(\frac{1 + q_s}{1 + q_w}\right)$$

q_s $= p_{sh} \times \sigma_{sh} / F_c$, $q_w = p_w \times \sigma_{wy} / F_c$

k =1.69 (shear-failure type),

k =1.65 (flexural-failure type)

t : thickness of the attached walls

h : total length column

Fc : concrete compressive strength

$$ {}_cQ_{su} = b \cdot j_t \cdot \sum (p_w \cdot \sigma_w) \cot\phi + \tan\theta \cdot (1 - \beta) \cdot b \cdot D \cdot \nu \cdot {}_c\sigma_B / 2 \qquad (2)$$

but when

$$\sum (p_w \cdot \sigma_w) > \nu_c \cdot \sigma_B / 2 , \qquad \sum (p_w \cdot \sigma_w) = \nu_c \cdot \sigma_B / 2$$

$$\tan\theta = \sqrt{(H/D)^2 + 1} - H/D \qquad \beta = \{(1 + \cot^2\phi) \cdot \sum (p_w \cdot \sigma_w)\} / (\nu_c \cdot \sigma_B)$$

$$\sum (p_w \cdot \sigma_B) = p_w \cdot \sigma_{wy} + \nu_{CF} \cdot (p_{wf} \cdot \sigma_{wf})$$

$$\nu_{CF} = 1.0 \qquad \left(2.12 < \frac{\sum (p_w \cdot \sigma_w)_0}{\sqrt{\sigma_B}} < 4.90\right)$$

$$= 3.13 \frac{\sqrt{\sigma_B}}{\sum (p_w \cdot \sigma_w)_0} \qquad \left(\frac{\sum (p_w \cdot \sigma_w)_0}{\sqrt{\sigma_B}} < 2.12\right)$$

$$= -0.13 \frac{\sum (p_w \cdot \sigma_w)_0}{\sqrt{\sigma_B}} + 1.28 \qquad \left(\frac{\sum (p_w \cdot \sigma_w)_0}{\sqrt{\sigma_B}} \geq 4.90\right)$$

$$\sum (p_w \cdot \sigma_w)_0 = p_w \cdot \sigma_{wy} + p_{wf} \cdot \sigma_{wf}$$

$$\cot\phi = \min \{2.0, j_t / (D\tan\theta) , \sqrt{\nu_c \cdot \sigma_B / \sum (p_w \cdot \sigma_w) - 1.0}\}$$

σ_{wy}	: yield strength of lateral reinforcement
σ_{wf}	: ultimate strength of the CFRP sheet (=2350MPa)
σ_{sh}	: yield strength of waist-high wall bars
p_w	: shear reinforcement ratio of the lateral reinforcement
p_{wf}	: shear reinforcement ratio of the CFRP sheet
p_{sh}	: shear reinforcement ratio within the wall
v_c	: effective concrete compressive strength (=0.7-σ_B/2000)
v_{cf}	: effective ultimate strength of CFRP sheet (=0.6)
ϕ	: angle of the concrete compressive strut in the truss mechanism
j_t	: *7/8 d*

Calculated shear strength *cQsu* versus observed maximum load *eQsu* relationship are shown in Fig. 8. Y and X axis values are standardized by calculated bending strength *cQmu*. The adaptability of the use of column height (*hc, he, h*) in the calculation of the bending and shear strength is investigated. Three figures correspond to the cases of h, h_e and h_c for calculate strengths. It can be observed that there is a good correspondence between the calculated and experimental values when *he* is used for column height. However, for specimens having a high axial force (No.4-2), further investigation on the use of *he* is necessary.

Energy Absorption Capacity

It is known that the absorbed energy represents the seismic capacity of the specimens directly. Transitions of absorbed energy (*Eac*) for each specimen are shown in Fig. 6. The specimens, which are strengthened using CF-anchor (No.1-1,No.1-2, No.1-3), show an increase in the energy absorption capacity as the amount of CFRP is increased. Taking specimens No.1-1 as the bases, it is observed that the capacity of specimens No.1-2 is increased to about 1.3 times, and that of No.1-3 to about 1.5 times. On the other hand, with regard to specimens No.1-2, No.2-2, No.3-2 and No.5-2, because of the similarity in the *Eac* curves, it can be stated that the height and the position of the attached walls dose little influence the energy absorption capacity of the columns. However, for the specimen having a great wall thickness (No.2-2), the *Eac* is greatly reduced at R= 1/20 radians. The specimen where only the column is strengthened (No.1-C2) and the specimen whose axial force is higher (No.4-2) show higher *Eac* than that of specimen No.1-2 before reaching the loading angle at failure. Also the capacity of specimen No.4-2 is increased to about 1.4 times of No.1-2 before failure. The specimen whose main bar is round steel bars (No.6-2) shows a lower capacity than specimen No.1-2 reduced to about 80%. Therefore, the ductility of the column can be improved greatly by the strengthening with CF-anchor.

Strain Distribution

Fig. 7 shows the strain distributions for the sheet and CF-anchors at the peak of each loading cycle. The left graphs show the distribution for sheets and CF-anchors at the perpendicular side to the loading direction, and the right ones show those of the parallel side. The dotted lines in the figures indicate the yield strain of hoops.

In the most of the specimens, the average strains in the sheets are larger than yield strain of hoops. This shows that the strengthening method using CFRP sheets is effective. Also, the strains in the sheets are observed to decrease as the amount of CFRP sheets is increased. The observed strains in the CF-anchors are smaller than 2000μ.

CONCLUSIONS

1. There is a great improvement in the ductility of the shear-failure type specimens when strengthened CFRP sheet. Also with an increase in the amount of the sheets, the ductility is further enhanced.

2. The specimens strengthened using CF-anchor also show higher ductility than the specimen where only the column is strengthened.

3. The bending strength and shear strength of reinforced concrete columns with waist-high walls can be calculated using the effective column height *he*. But for cases of a high axial force, the good correlation between calculated and experimented values is not observed.

4. The specimens not using CFRP sheets, it was observed that the toughness of the columns is decreased as the wall thickness, height and eccentricity of the wall is increased. Moreover, for specimen strengthened by CFRP sheets, a decrease in the toughness of the column is also observed as the thickness and height of the wall is increased. However, there is an increase in the toughness of the column as the eccentricity of the wall is increased.

5. The observed strains in the CF-anchor are lower than 2000μ which shows that the CF-anchor has enough factor of safety comparing it to the ultimate strength of the CFRP sheets.

ACKNOWLEDGMENT

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REFERENCES

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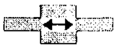
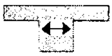
TABLE 1—LIST OF SPECIMENS.

<table>
<tr><th>Specimen</th><th>Section</th><th>Main bars</th><th>Axial force (kN)</th><th>Effective height h_e (cm)*</th><th>Height of walls h_w (cm)</th><th>Thickness of walls t_w (cm)</th><th>Sheet weight (g/m^2)×layer</th></tr>
<tr><td>No.1-0</td><td rowspan="10"></td><td rowspan="12">4-D13</td><td rowspan="9">424</td><td rowspan="5">64.3</td><td rowspan="7">30</td><td rowspan="5">7.5</td><td>-</td></tr>
<tr><td>No.1-1</td><td>150×1</td></tr>
<tr><td>No.1-2</td><td>300×1</td></tr>
<tr><td>No.1-3</td><td>150×1
300×1</td></tr>
<tr><td>No.1-C2</td><td>300×1
only column</td></tr>
<tr><td>No.2-0</td><td rowspan="2">60.5</td><td rowspan="2">10</td><td>-</td></tr>
<tr><td>No.2-2</td><td>300×1</td></tr>
<tr><td>No.3-0</td><td rowspan="2">51.4</td><td rowspan="2">45</td><td rowspan="6">7.5</td><td>-</td></tr>
<tr><td>No.3-2</td><td>300×1</td></tr>
<tr><td>No.4-2</td><td>951</td><td rowspan="4">64.3</td><td rowspan="4">30</td><td>300×1</td></tr>
<tr><td>No.5-0</td><td rowspan="2"></td><td rowspan="3">424</td><td>-</td></tr>
<tr><td>No.5-2</td><td>300×1</td></tr>
<tr><td>No.6-2</td><td></td><td>4-ϕ13</td><td>300×1</td></tr>
</table>

$* \frac{h_e}{h}=1-k\left(1-\frac{h_c}{h}\right)\sqrt{\frac{t}{b}}\left(\frac{1+q_s}{1+q_w}\right)$ $q_s=p_{sh}\times\sigma_{sy}/F_c$, $q_w=p_w\times\sigma_{wy}/F_c$,

k=1.69(Shear-failure type), k=1.65(Flexural-failure type)

TABLE 2—MECHANICAL PROPERTIES OF CONCRETE.

<table>
<tr><th>Type</th><th>Compressive strength σ_B (MPa)</th><th>Splitting strength σ_{SP} (MPa)</th><th>Elastic modulus E_c (GPa)</th><th>Specimen</th></tr>
<tr><td rowspan="2">Normal</td><td>25.2</td><td>2.49</td><td>23.0</td><td>No.1-0
No.1-C2</td></tr>
<tr><td>27.4</td><td>2.49</td><td>25.4</td><td>No.1-1～1-3</td></tr>
<tr><td rowspan="4">Normal</td><td>25.2</td><td>2.02</td><td>22.2</td><td>No.2-0
No.3-0</td></tr>
<tr><td>22.3</td><td>1.96</td><td>21.1</td><td>No.5-0</td></tr>
<tr><td>26.8</td><td>2.25</td><td>24.6</td><td>No.4-2
No.2-2
No.3-2</td></tr>
<tr><td>25.8</td><td>2.06</td><td>24.0</td><td>No.5-2
No.6-2</td></tr>
</table>

TABLE 3—MECHANICAL PROPERTIES OF REINFORCEMENT.

Identification (Nominal diameter)	Ultimate strength σ_{su} (MPa)	Yield strength σ_{sy} (MPa)	Elastic modulus E_s (GPa)	Specimen
D13 (13mm)	494	341	185	No.1-0～5-2
ϕ13 (13mm)	457	325	203	No.6-2
D6 (6mm)	532	413	193	No.1-0～6-2
D4 (4mm)	385	250	211	No.1-0～6-2

TABLE 4—MECHANICAL PROPERTIES OF CARBON FIBER SHEETS.

Weight per unit area (g/m^2)	Thickness (mm)	Specific gravity (g/cm^3)	Ultimate strength σ_{fu} (MPa)	Elastic modulus E_f (GPa)
150	0.835	1.80	4500	273
306	0.167	1.80	4170	257

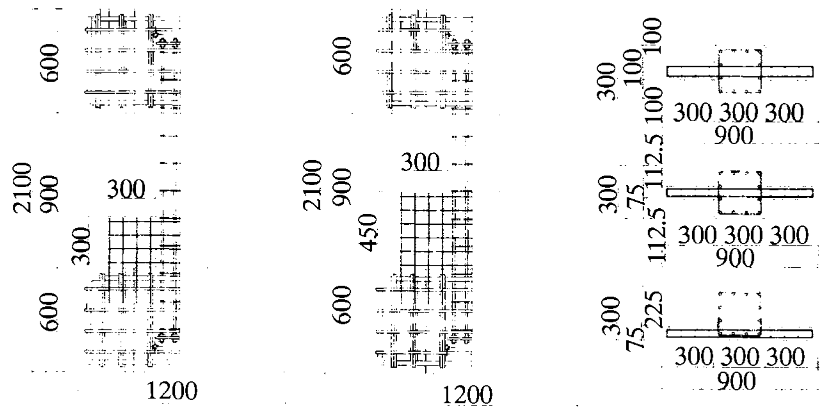
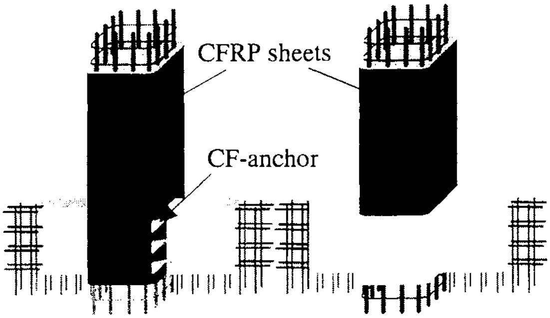


Fig. 1—Dimensions of specimens (unit: mm).



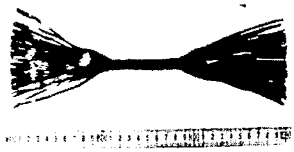


Photo 3 CF-anchor

Fig. 2—Method of reinforcing.

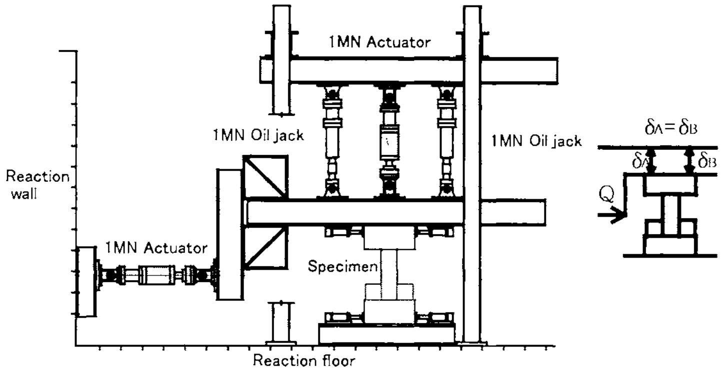
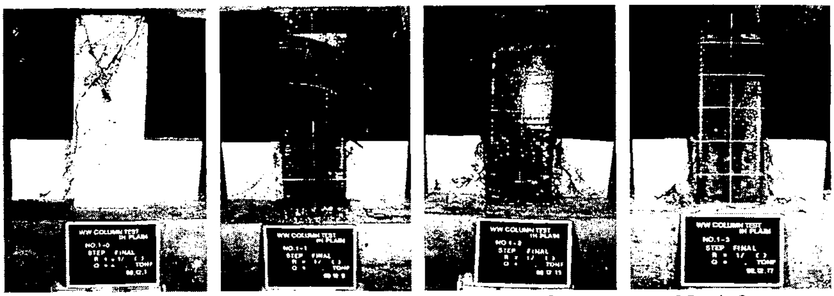


Fig. 3—Asymmetrical loading system.



No.1-0 No.1-1 No.1-2 No.1-3

Fig. 4—Specimens after loading.

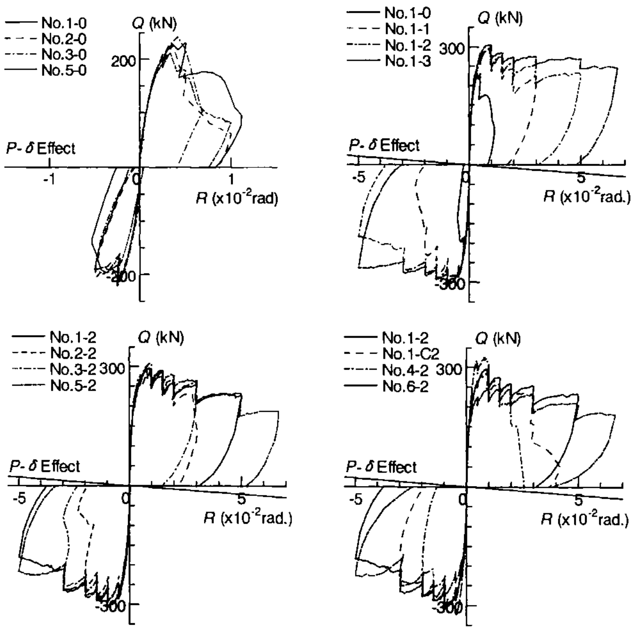


Fig. 5—Shear force—drift angle skeleton curves.

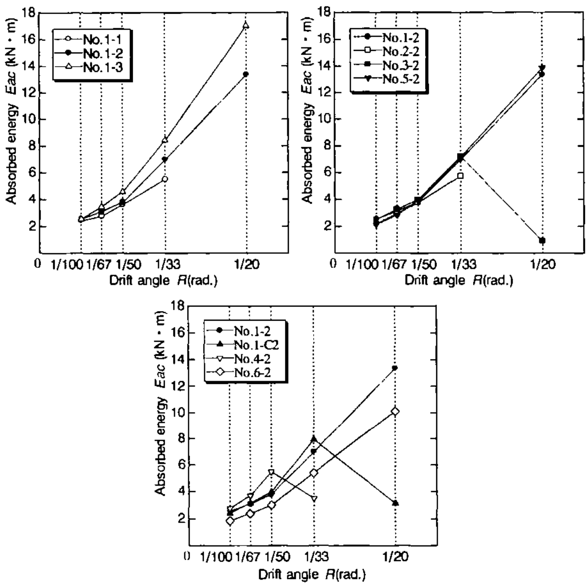


Fig. 6—Transition of absorbed energy.

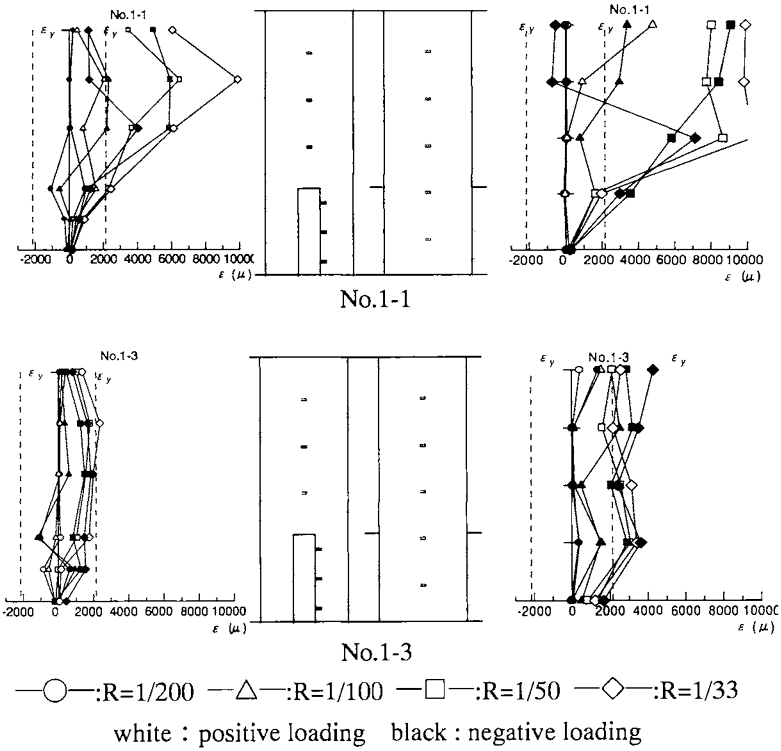


Fig. 7—Strain distribution in sheets and CF anchors.

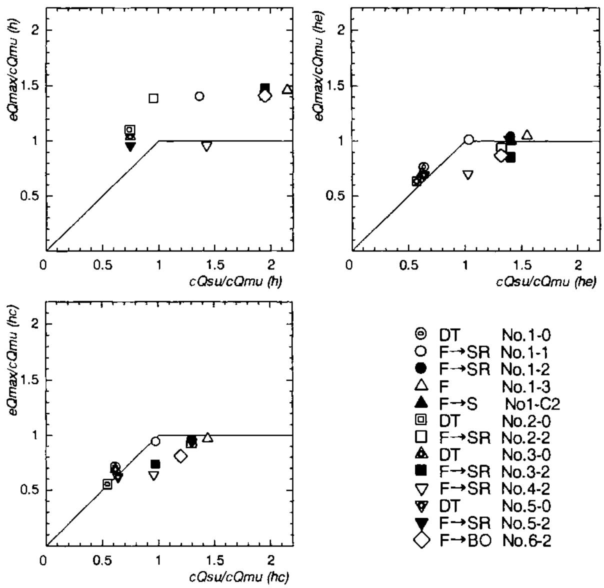


Fig. 8—Calculated shear force *cQsu* - maximum load *eQsu.*