DUCTILITY OF T-SHAPE RC BEAMES STRENGTHENED BY CFRP SHEET

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ABSTRACT

This study presents the results of strengthening using CFRP (Carbon Fiber Reinforced Plastic) sheet. 15 T-shape reinforced concrete beams were strengthened and tested. The main objective is to investigate the effect of strengthening using CFRP sheet with several anchoring types on the maximum load and ductility of the beams. 9 beams which were designed to be governed by shear failure, and the other 6 specimens were flexural-failure type. Test results show that in shear-failure type beams, the maximum load increases by 20 - 60% with corresponding increase when strengthened using CFRP. Compared to a continuous anchor plate, higher ductility is obtained when the strengthening was done using staggered anchor plates. The specimens with angle anchor plates also show higher ductility rather than the specimens anchored with staggered plates.
KEYWORDS : RC beam, T-shape, CFRP (carbon fiber reinforced plastic), ductility, anchor

1. INTRODUCTION

The South Hyogo Earthquake, which occurred at January 17, 1995 in Japan, damaged a quite number of structures, such as buildings, wooden houses, bridges, offshore constructions, and so on. The magnitude and depth was 7.2 and 20 km, and the mechanism was fault sliding. The epicenter was positioned quite near to the city of Kobe, which is one of the oldest cities in Japan. The maximum acceleration of over 800 gal was observed at JMA Kobe.

Many reinforced concrete buildings were also damaged by this earthquake. Photo 1 shows the typical example of damaged buildings with pilotis. This office building was constructed 1960's. Round steel bars are used both for main bars and hoops, and the arrangement of hoops are very poor.

Photo 1 Damaged four-story pilotis building

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An apartment building shown in Photo 2 was built in 1980's. Although this building did not destroyed in a whole, many cracks were observed in beams and secondary structures. Especially for beams, shear failure and bond splitting failure were recognized, and cover concrete fell down.

Photo 2 Damaged nine-story apartment building

In Japan, two major revisions of the standard law for RC buildings were carried out. The first revision was in 1970, that was after Tokachi Earthquake in 1968. In this revision, maximum spacing of hoops were restrained under 10 cm from 30 cm. The second revision was carried out in 1981, that was also after Miyagi Earthquake in 1978. This revision is still effective in the present law. After 1981, it is necessary to calculate the capacity at the mechanism that is provided by the combination of strong columns and weak beams. This changes of the law cause the differences of damage levels by constructed years. In addition, it is considered that the present law is most enough for seismic performance. However, a huge number of buildings constructed before 1981 are still exist in all over Japan. If the earthquake with same scale of last earthquake occur in another city, a lot of buildings will be destroyed. It is quite necessary to strengthen or upgrade old buildings constructed before 1981.

Two methods for strengthening or upgrading have been popular in Japan. One is the increasing of sectional area by post-casting concrete, and the other is the confining of members by steel plates. These methods, however, need many processes, much time, good techniques and heavy machines. Recently, strengthening method using continuous fiber, such as carbon, glass and aramid have been focused because of its simplicity for construction site and economy. The simplest way to use fiber for strengthening is wrapping of members by sheets. Many investigations and studies concerning with fiber sheet strengthening are now going on both for building and civil engineering site in Japan.

In case of columns, it is easy to wrap them. The fiber sheets carried shear force directly, and confinement effect is also expected. In case of beams, it is not so easy to wrap, because ordinary beams have floor slabs. Therefore, the development of sheet anchoring method is important to use fiber sheets effectively. In this paper, to investigate the effect of anchoring method differences, the results of loading test for 15 T-shape beams are reported. Test variables are sheet anchoring method and stirrup ratio for pre-strengthened beams. Test results are mainly discussed about the ductility of specimens.

2. TEST PROGRAMS

2.1 SPECIMENS

15 T-shape RC beams are tested. The list of specimens and dimensions of them are presented in Table 1 and Fig. 1, respectively. The cross section is 200 mm in width and 300 mm in depth, designed at half scale of actual size beams. Clear span length is 1200 mm, and shear span ratio is 2.0. Specimens have slabs at both sides of beams. Arrangements of main bars are common in all specimens, that is 5-D13 with specified yield strength of 300MPa class. In specimen number from 11 to 14 and from 21 to 25, D4 reinforcement are arranged with spacing of 70mm. In other specimens, D6 reinforcement is used also with 70mm spacing. Specified concrete strength is 18MPa, that was mainly used in buildings constructed in 1960's.

Carbon fiber reinforced plastic (CFRP) sheet is used for strengthening the beam. The weight per unit area is 200g/m^2. Strength and elastic modulus of CFRP is 4750MPa and 229GPa, respectively. Test variable is anchoring methods of CFRP. As shown in Fig. 1, 6 types of anchor are chosen. In type A, CFRP is anchored with only epoxy resin under the all surface of slabs. In type B, CFRP is anchored with continuous plates which are tightened to anchor bolts buried at the sides of beam with spacing in 140mm or 70mm. In type C, staggered plates which are separated into 9 or 18 pieces for each side are used for anchor. In type D, staggered angle plates which are tightened to anchor bolts buried both at the side of beam and at the surface of slab are used. Type D' is the specimen strengthened by same angle without CFRP. In type E, staggered angle plates are tightened to anchor bolts buried only at the slab surface. In type F, anchor bolts are fixed by nuts at the upper surface of slab through holes.

Mechanical properties of CFRP sheet, reinforcement and concrete are presented in Table 2, 3 and 4.

Table 1 List of specimens

	Section, Main bars	Stirrup		CFRP sheet		Anchor method
		Reinforcement	p_w(%)	weight	Σp_w(%)*	
No.11	200×300mm 5-D13 p_t=1.23%	2-D4@70	0.18	-	0.18	-
No.12				200g/m^2	0.58	B : continuous plate
No.13						A : slab surface
No.14						C : staggered plate
No.15		2-D6@70	0.46	-	0.46	-
No.16				200g/m^2	0.78	B : continuous plate
No.17						A : slab surface
No.21		2-D4@70	0.18	-	0.18	D' : angle with both bolts
No.22				200g/m^2	0.68	D : angle with both bolt
No.23						E : angle with beam bolt
No.24						F : angle with through bolt
No.25						C : staggered plate
No.26		2-D6@70	0.46	-	0.46	D' : angle with both bolts
No.27				200g/m^2	0.78	D : angle with both bolts
No.28						C : staggered plate

* $\Sigma p_w = p_w+(f_f/f_s)p_{wf}$: f_f = specified strength of CFRP, f_s = yield strength of stirrup, p_{wf} = ratio of CFRP

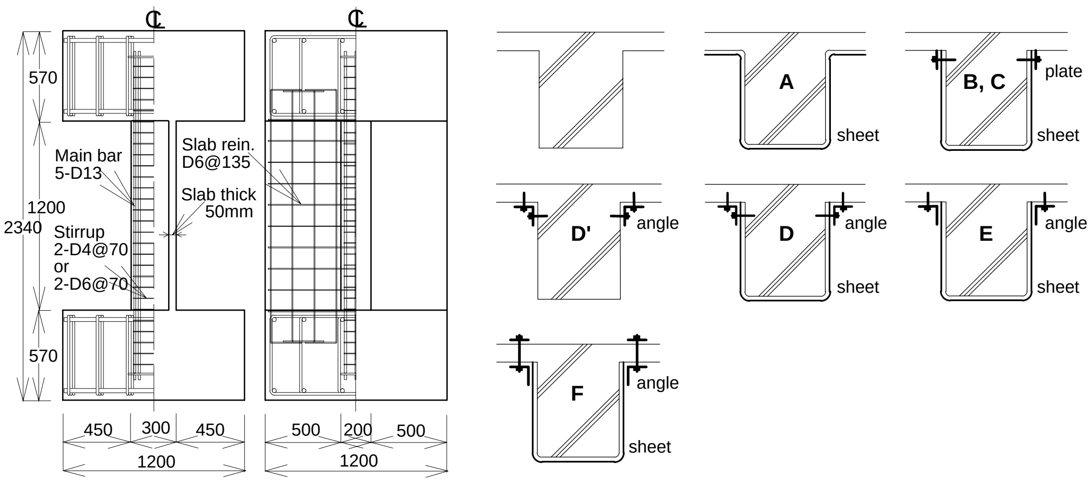


Fig. 1 Dimensions of specimens

Table 2 Mechanical properties of CFRP sheet

Weight per unit area (g/m^2)	Thickness (mm)	Width of unit sheet (mm)	Ultimate strength f_{fu} (MPa)	Elastic modulus E_f (GPa)
200	0.114	250.5	4747	229

Table 3 Mechanical properties of reinforcement

Identification (Nominal diameter)	Yield strength f_s (MPa)	Ultimate strength f_{su} (MPa)	Elastic modulus E_s (Gpa)	Specimen
D13 (13mm)	330 337	463 488	182 180	No.11～17 No.21～28
D6 (6mm)	354* 336*	533 520	185 177	No.11～17 No.21～28
D4 (4mm)	272 218	342 332	214 199	No.11～17 No.21～28

* 0.2%offset

Table 4 Mechanical properties of concrete

Type	Compressive strength f_c (MPa)	Splitting strength f_{ct} (MPa)	Elastic modulus E_c (GPa)
Normal	16.8～21.8	1.34～1.53	18.6～21.8

2.2 LOADING PROGRAMS

Antisymmetrical cyclic load is provided for all specimens using the antisymmetrical loading system as shown in Fig. 2. The loading is carried out by controlling translational angle (R). The loading history to be applied to all specimens is R = ±1/400 radians once, R = ±1/200, ±1/100, ±1/50, ±1/33 radians twice and R = ±1/20, +1/15 radians once. Shear force, relative displacement between the upper and the lower stub and strains of reinforcements and CFRP sheet are measured.

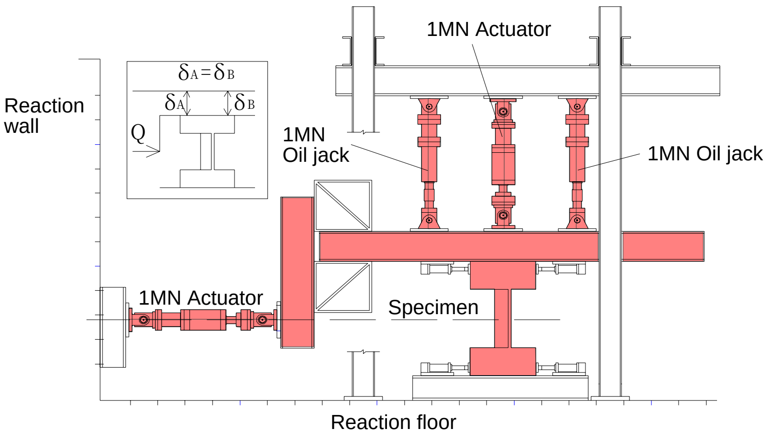


Fig. 2 Antisymmetrical loading system

3. TEST RESULTS

3.1 FAILURE PROGRESS

Test results and some calculated values are listed in Table 5. Following formulas are used to calculate bending and shear strength. Stirrup ratio, p_w, is modified into Σp_w to evaluate the effect of CFRP sheet.

$$ {}_cQ_{mu} = 0.9\Sigma(a_t \cdot f_b \cdot d)/(L_0/2) \quad (1) $$

$$ {}_cQ_{su} = \left[\frac{0.115k_u \cdot p_t^{0.23}(180 + f_c)}{M/Q \cdot d + 0.115} + 2.7\sqrt{\Sigma p_w \cdot f_s} \right] \cdot b \cdot j \tag{2} $$

where,

${}_cQ_{mu}$	: calculated bending strength
${}_cQ_{su}$	: calculated shear strength (kgf)
a_t	: sectional are of tensioned main bars
f_b	: yield strength of main bars
d	: effective depth
L_0	: clear span length
k_u	: reduction factor due to sectional size
p_t	: ratio of tensioned main bars (%)
f_c	: concrete compressive strength (kgf/cm^2)
M/Q	: shear span length
Σp_w	: stirrup ratio including effect of sheet
f_s	: yield strength of stirrup (kgf/cm^2)
b	: width
j	: $= 7/8\, d$

The failure progresses until the loading cycle to R = 1/200 radians were almost the same in all specimens. First, bending cracks took place at the both ends of beams and they expanded, as the displacement became larger. Next, shear cracks took place.

In specimen No.11, shear cracks expanded at the loading cycle to R = 1/100 radians and applied shear force did not increase. Yielding of stirrups and the maximum loads were also recognized at the same cycle. This specimen showed brittle behavior and yielding of main bars were not observed. This failure is defined as shear tension failure (ST). Other specimens had yielding of main bars (F) at the loading cycle to R = 1/100 radians. In specimens No.12 and No.16, continuous anchor plates restricted the deformation of beams and the slab separated from the beam. This failure is defined as slab separated failure (BS). In specimens No.13 and 17, sheet was peeled at the corner between slabs and beam with separating slab and beam. Shear cracks also recognized. In specimens No.14 and No.28, staggered anchor plates did not restrict the deformation of beam. Some shear cracks were recognized and concrete at the ends of beams was crushed. This failure is defined as shear compression failure (SC). In specimen No.25 which was also anchored by staggered plates, cracks between slab and beam expanded and failed by slab separated failure and anchor bolts fell down with concrete (AF). In specimens from No.21 to No.24 and No.26, 27,

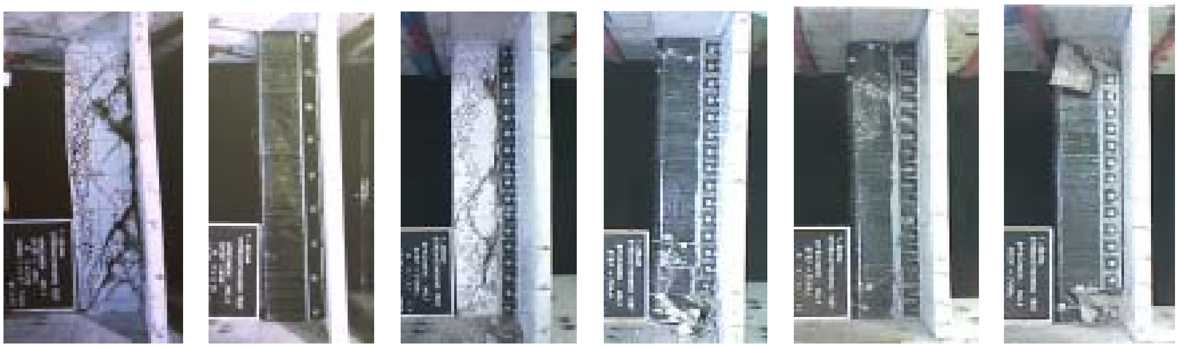
Table 5 List of test results

Spec-imen	Shear strength *cQsu* (kN)	*cQsu / cQmu*	Yield strength *eQy* (kN)	Maximum shear force *eQmax* (kN)	*eQy / cQmu*	*eQmax/ cQmu*	Yield angle *Ry* (rad.)	Ultimate angle *Ru* (rad.)	Ultimate ductility $\mu = Ru/Ry$	Failure mode
No.11	80.6	0.80		76.7		0.76		1/23		ST
No.12	102	1.01	102	105	1.01	1.04	1/154	1/37	4.19	F→BS
No.13	109	1.07	87	95	0.86	0.94	1/214	1/50	4.27	F→ST,BS
No.14	109	1.07	96	105	0.95	1.04	1/185	1/25	7.46	F→SC
No.15	101	1.00	107	112	1.06	1.11	1/98	1/23	4.33	F→BS
No.16	116	1.14	110	113	1.09	1.12	1/99	1/19	5.25	F→BS
No.17	116	1.14	111	116	1.10	1.15	1/115	1/22	5.29	F→ST,BS
No.21	82.5	0.81	91.2	99.4	0.89	0.97	1/207	1/20	10.4	F→ST
No.22	106	1.04	102	123	1.00	1.20	1/179	1/22	8.06	F→SR
No.23	106	1.04	118	122	1.15	1.19	1/129	1/31	4.14	F→AF
No.24	106	1.04	126	126	1.23	1.23	1/97	1/19	5.15	F→SR
No.25	104	1.01	102	105	1.00	1.03	1/158	1/30	5.22	F→BS→AF
No.26	104	1.02	115	118	1.12	1.16	1/117	1/19	5.98	F→SC
No.27	120	1.17	120	122	1.17	1.19	1/105	1/20	5.35	F→SR
No.28	120	1.17	109	118	1.07	1.15	1/136	1/21	6.38	F→BS→AF

note : *cQmu*=102 (kN)

F : bending yielding BS : slab separated failure SC : shear compression failure ST : shear tension failure

SR : sheet rupture AF : anchor failure



No.11 No.12 No.21 No.22 No.24 No.25

Photo 3 Failure pattern of typical specimens

these were strengthened by angles, slab separated failure was not observed. Specimen No.21 showed the shear failure after yielding of main bars. In specimens No.22, 24 and 27, rupture of sheet (SR) was recognized with the remarkable decrement of shear force. Anchor bolts of specimen No.23 fell down with concrete block. Side view of typical specimens after loading is shown in Photo 3.

3.2 COMPARISSON OF SHEAR FORCE – TRANSLATIONAL ANGLE SKELETON CURVES

Shear force versus translational angle skeleton curves of specimens are shown in Fig. 3. In specimens from No.12 to No.14 and from No.21 to 25 which are strengthened specimens with p_w of 0.18%, maximum loads and peak loads of each loading cycles increase compared with no-strengthened specimen No.11. The increase ratio in maximum load ranged from 20% to 60%. The maximum load of specimen No.14 which was strengthened by staggered plates is bigger than that of specimen No.12 which was strengthened by continuous plates. While the translational angle at the maximum load of specimens No.21, 22, 23 and 25 is around 1/100 – 1/50 radians, that of specimen No.24 is 1/20 radians. In specimens No.16, 17, 26, 27 and 28, which are strengthened specimens with p_w of 0.46%, a slight increment of maximum loads is recognized. Because yielding of main bars in these specimens was observed.

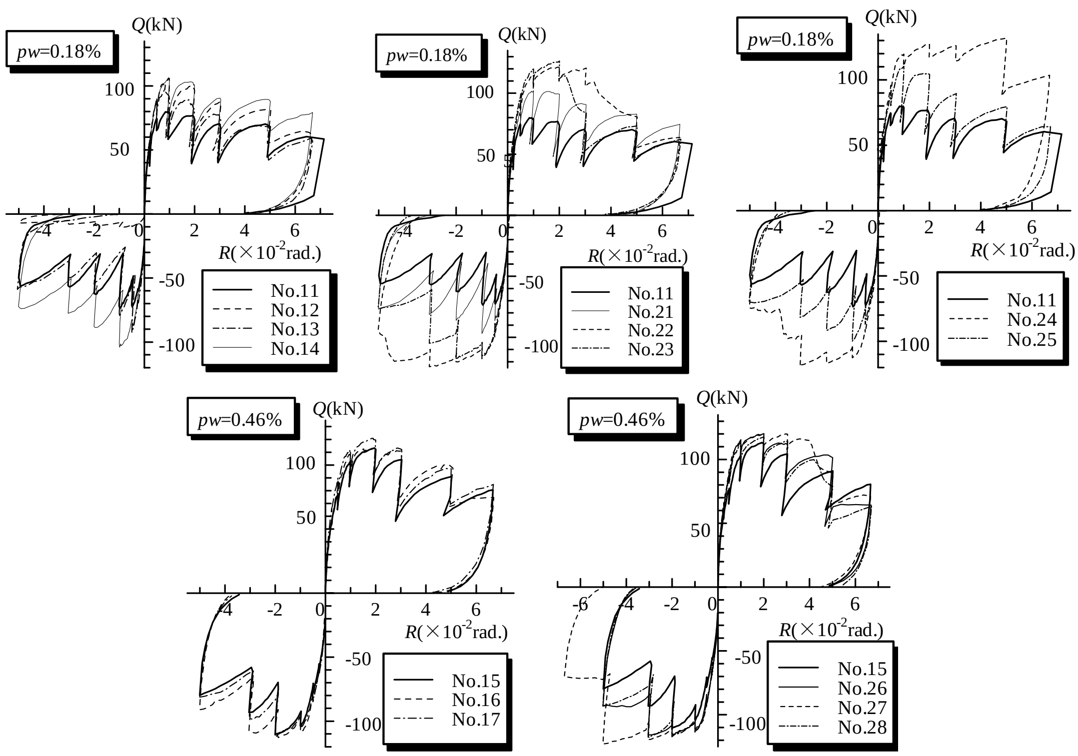


Fig. 3 Shear force - translational angle skeleton curves

4. DISCUSSIONS

4.1 ENERGY ABSORPTION CAPACITY

It is recognized that the absorbed energy represents the seismic capacity of RC members directly. Transitions of absorbed energy (*Eac*) for each specimen are presented in Fig. 4. *Eac* of specimens which are strengthened by type A anchor method (No.13 and No.17) dose not much differ from that of no-strengthened specimens (No.11 and No.15). Specimens strengthened by anchor plates show high energy absorption capacity. That capacity of specimens No.12, 14 and 25 is increased to about 1.5 times of No.11. On the other hand, Speci-mens strengthened by angle plates show very high energy absorption capacity. That capacity of speci-mens No.22, 23 and 24 is increased to from 2.8 to 3.6 times of No.11. In addition, the capacity of No.24 is bigger than that of No.23. Ductility can be much improved by the strengthening with section closed type anchoring (type F).

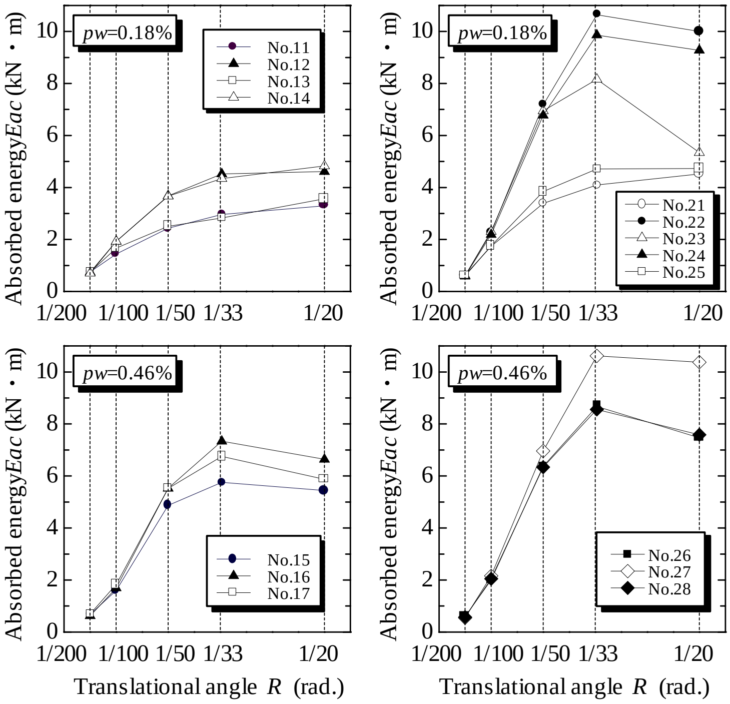


Fig. 4 Transition of absorbed energy

4.2 STRAIN DISTRIBUTION

Fig. 5 presents strain distributions for stirrups and sheet at the peaks of loading cycles. The left graphs show the strains of stirrups, and the right ones show strains of sheet. Upper graphs are of specimen No.24 and lower ones are No.25. Strains of stirrups exceed yield strain (ε_y) at the loading cycles of 1/200 radians. Though stirrup ratio of No.24 is same as that of No.25, the average strains of No.24 is smaller than that of No.25. Instead of that phenomenon, the average strain of sheet for No.24 is bigger than No.25. It is considered that this difference is influenced by the difference of strengthening effect due to anchoring method. In specimen No.24, strengthening effect is higher than other specimens.

5. CONCLUSIONS

(1) The maximum load of specimens with p_w of 0.18% increases comparing with that of no-strengthened specimen. The increase ratio ranged from 20% to 60%. Energy absorption capacity of strengthened specimens also increases to 1.5 – 3.6 times of no-strengthened specimen.

(2) Energy absorption capacity of strengthened specimens with p_w of 0.46% increases to 1.2 – 1.8 times of

no-strengthened specimen.

(3) Staggered plates anchor improves the behavior more ductile than that of continuous plates anchor specimens. Continuous plates anchor restricts the deformation of beam. As a result, the beam separates from slab.

(4) Specimens strengthened by angle plates anchor show the most ductile behavior. Ductility can be much improved by the strengthening with section closed type anchoring.

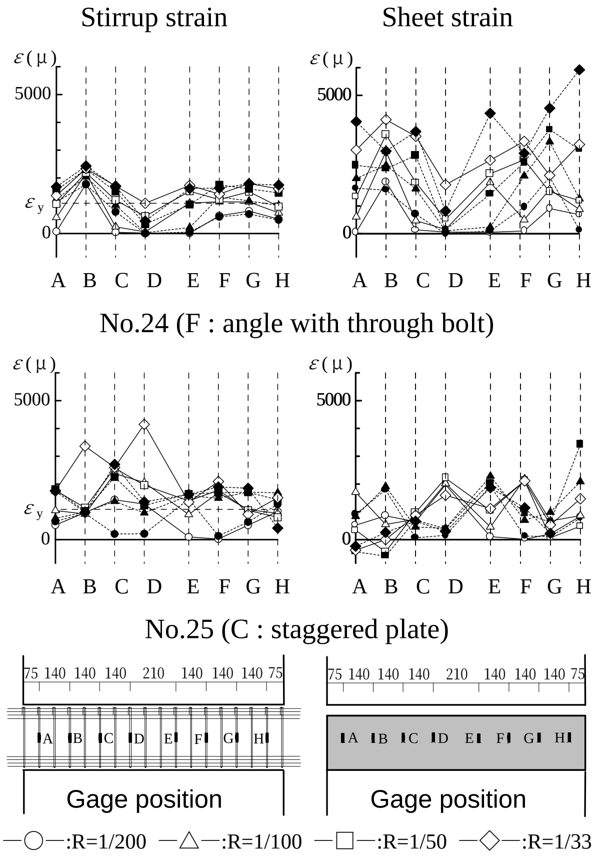


Fig. 5 Strain distribution of stirrups and sheet