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THE BEAM RETROFITTED BY CARBON FIBER-EXPERIMENT AND DESIGNS

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SUMMARY

This paper describes structural performance and a design method of existing beams that are strengthened with carbon fiber sheets against an earthquake load. A loading test shows that shear strength of beams can be improved by transverse wrapping of carbon fiber sheets when anchoring of the sheets are provided by steel plates and bolts, even if longitudinal bars are not completely enclosed. An equation for calculating the shear strength is proposed using a macroscopic model based on the concept of the arch and the truss mechanism composed of two regions. The proposed model is also employed for calculating the bond strength and the sliding strength of slipping and separating failure between slab and beam. The accuracy of the proposed equations is demonstrated through comparisons of calculated strengths with experimental ones.

INTRODUCTION

There are some existing reinforced concrete buildings in which beams as well as columns [1] should be retrofitted not to fail in shear during an earthquake. The wrapping method with carbon fiber sheets is promising because of easy application works. Since a beam always has a slab, the slab obstructs to form closed type transverse reinforcement only with carbon fiber sheets. And strengthening effectiveness is not obtained in the way of sticking the carbon fiber sheets around a beam only [2]. So the authors developed a technique of fixing the carbon fiber sheets with plates and bolts to the both sides of the beam as shown in Fig. 1. This side-anchoring is preferable because this method does not require the application work at the upper floor. However, as carbon fiber sheets do not completely enclose top and bottom bars, the stress transfer mechanism at this method is different from that of ordinary reinforced concrete beams. In other words, the current design method cannot be applied for retrofitted beams with side-anchoring. Therefore, an equation for calculating the shear strength is proposed using a new macroscopic model based on the concept of the arch mechanism and the truss mechanism composed of two regions. Moreover the proposed model is employed equations for calculating the bond strength and the sliding strength of slipping and separating failure between slab and beam. This paper presents retrofitted methods for beams and estimating equations for shear, bond, and sliding strengths of retrofitted beams with side-anchoring.

EXPERIMENT

Test Specimens and Parameters:

Test specimens and the arrangement of reinforcement is shown in table 1 and Fig. 2, respectively. The reduction scale of the specimens is about 2/3. The specimens do not have slab to clarify failure modes. Considering the slab of actual beams, the anchoring bolts are located a little downwards from the top bars of the specimens. Test variables are an amount of carbon fiber sheets and the technique of fixing as shown in Fig. 3. In order to study strengthening effectiveness, all specimen is designed to fail in shear before flexural yielding of longitudinal bar. The fixing part is designed so that the shear yielding of anchoring bolt resists tensile strength of the carbon fiber sheet. Properties of used materials are shown in Table 2. As shown in Fig. 2, the employed loading system can produce the anti-symmetric stress state within the middle testing portion to simulate response under an earthquake load. Specimens were subjected to a monotonic load.

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Results:

Fig.4 shows relationships between shear force and displacement. All specimens failed in shear before flexural yielding of longitudinal bar. However, the shear strength of the retrofitted beams with one sheet was increased about twice of unretrofitted RC. The one with two sheets was improved more. Relationships between the average strain and deflection angle are shown in Fig.5. According to Fig.5, the average strain of carbon fiber sheet was between $8000*10^{-6}$ and $10,000*10^{-6}$ at maximum strength. On the basis of minimum strain, the strength of carbon fiber (${}_{cf}\sigma_{wy}$) was safely determined to be 1, 800kN/mm^2, employing elastic modulus. Observing situations after the test as shown in Fig.6, cracks of the unretrofitted RC occurred into diagonally, and the others occurred almost in the 45 degrees direction. These results were reflected in the design formula.

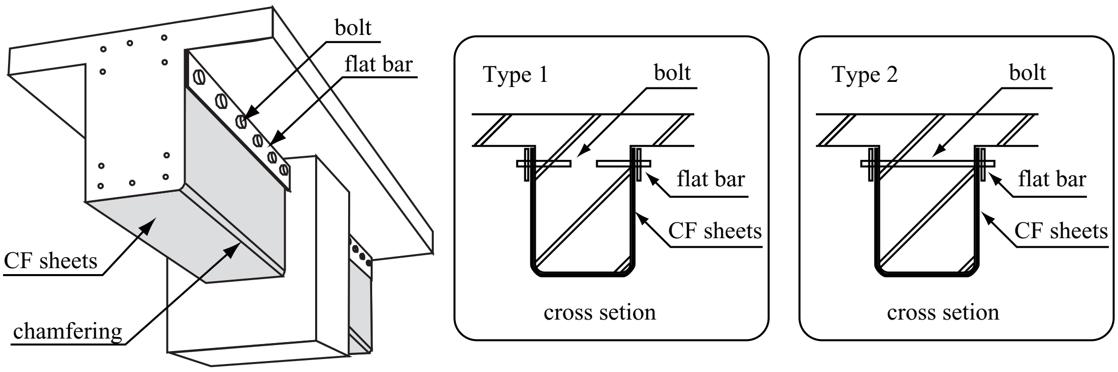

Fig.1 Seismic Retrofit for Beams

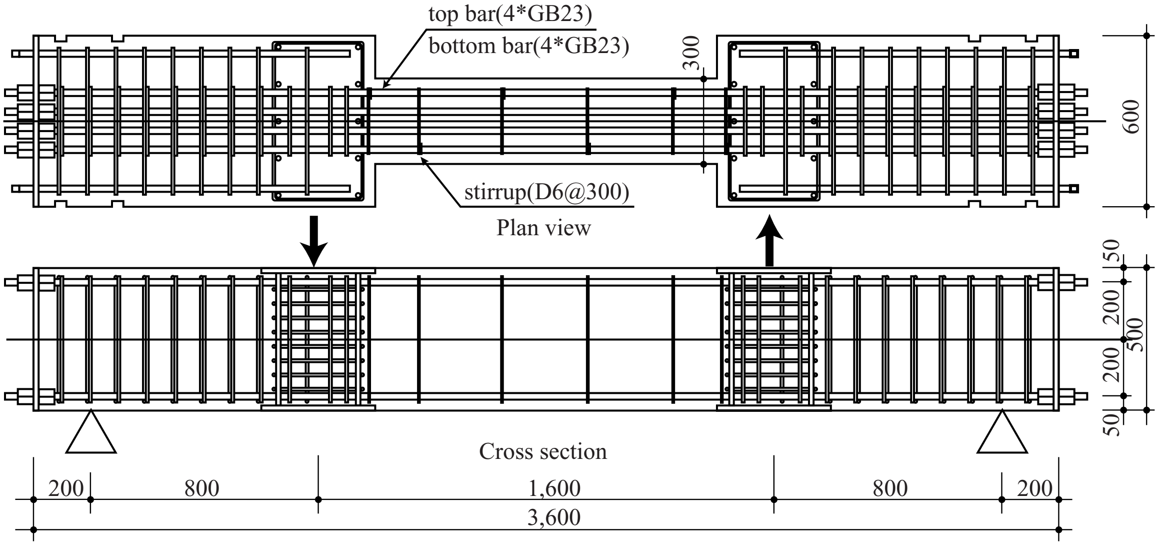

Fig. 2 Arrangement of reinforcement

Table 1 Summary tests

Specimen	σ_B (N/mm^2)	top and bottom bar	stirrup (p_w)	transverse CF ${}_{cf}p_w \cdot {}_{cf}\sigma_y$	anchoring	predicting failure
RC	24	4*GB23	D6@300 (0.062%)	-	-	shear failure
CF1-P				13.3	PC23@300	shear failure
CF2-P				26.6	PC26@200	shear failure
CF1-A1				13.3	M16@125	shear failure
CF1-A2				13.3	M16@200	shear failure

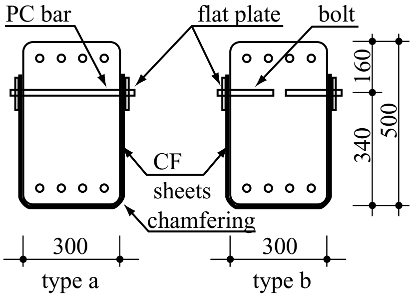

Fig. 3 Anchoring metods of CF sheets

Table 2 Material properties

	Elastic modulus (10^5N/mm^2)	Yielding strength (N/mm^2)	Yielding strain (10^{-6})	Rupture stress (N/mm^2)
concrete	0.223^{*1}	-	-	23.9^{*2}
axial bar	2.12	1030	6620	1170
stirrup	2.04	390	1910	535
CF sheet	2.58	-	-	3870
bolt(M16)	1.87	805	-	1111

*1:Secant modulus *2:Compressive strength

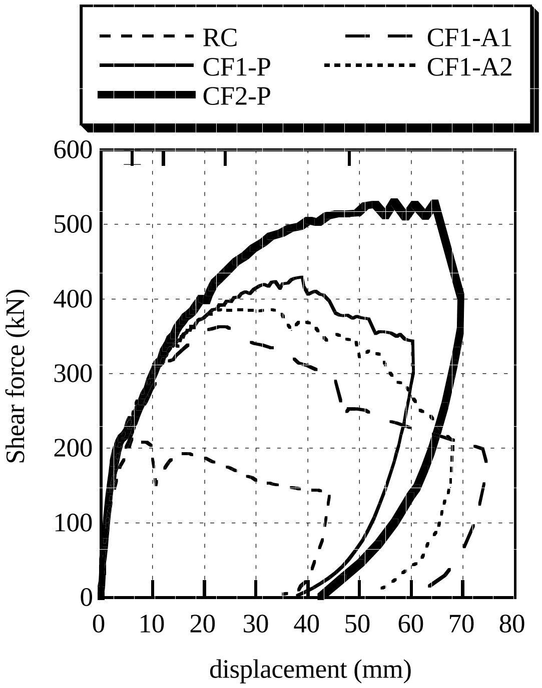

Fig. 4 Relationships between shear force and displacement

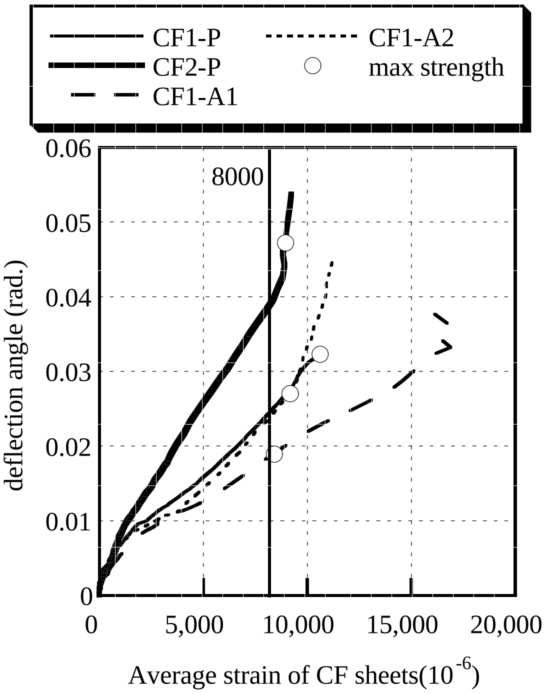

Fig. 5 Relationships between deflection angle and Average strain of CF sheets

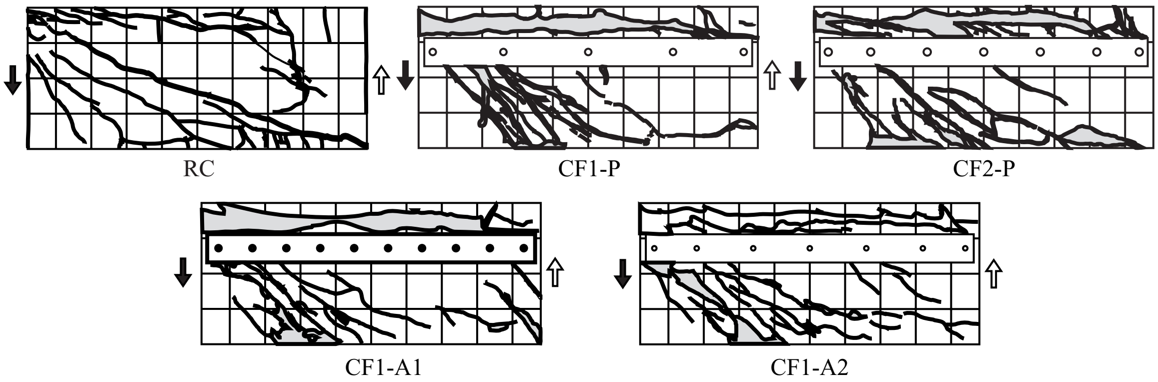

Fig.6 Crack patterns observed when peeling off the carbon fiber sheets after the test

CALCURATION STRENGTH OF A RETROFITTED BEAM

As shown in Fig. 7, the retrofitted beam with side-anchoring technique has some failure modes, which are shear failure and bond failure and sliding failure of slipping and separating failure between slab and beam. This chapter mentions a macroscopic model (Fig.8) commonly using each failure mode, and describes how to estimate each strength. This model is based the model [3] proposed by the Architectural Institute of Japan (AIJ), and obtained by modification for side-anchoring.

The concept of structural design is to make flexural failure precede to shear failure, bond failure and sliding failure. The principle of the anchoring design is to prevent anchoring failure prior to a break of carbon fiber sheets.

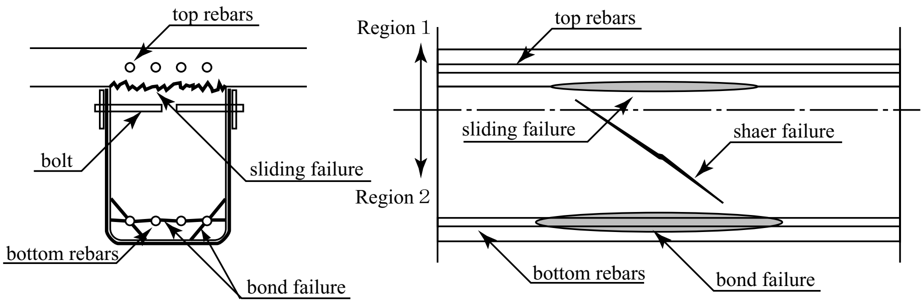

Fig.7 conceptual diagram of failure modes

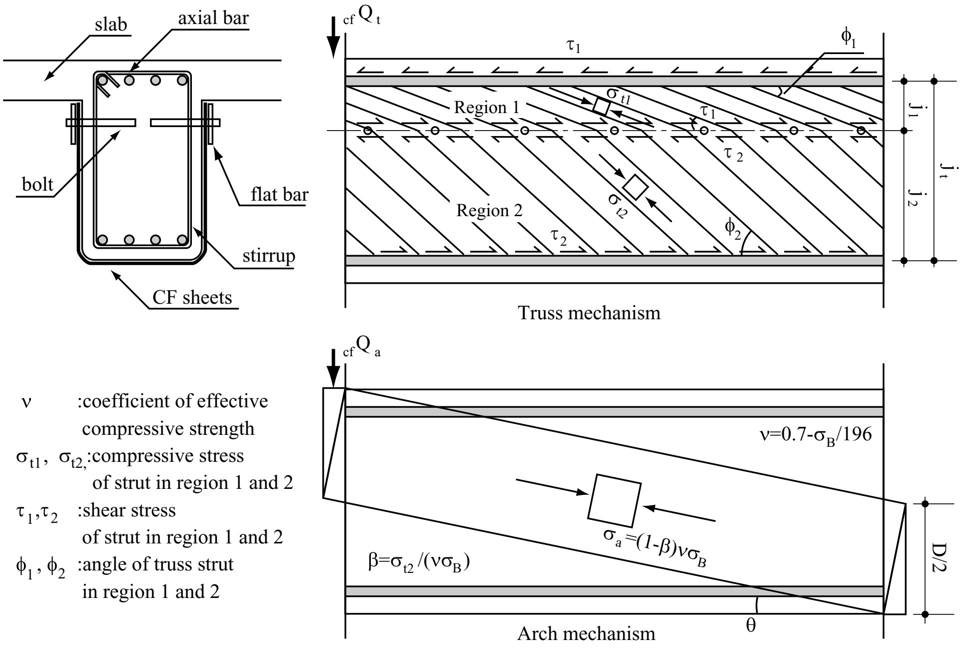

Fig.8 Macroscopic model

Shear strength:

The shear strength of the retrofitted beam is calculated by a new macroscopic model composed of the arch mechanism and the truss mechanism as shown in Fig. 8, and based on the concept of lower bound theorem in plastic theory. The assumptions of these calculations are as follows:

(A) External and internal forces are in equilibrium.

(B) The existing stirrup stress reaches yielding strength and carbon fiber sheet stress reaches ${}_{cf}\sigma_{wy}$ that is the value determined by tests results.

(C) The sum of compressive stress of the arch mechanism and the truss mechanism is equal to or less than effective compressive strength of concrete.

As for the arch mechanism, the stress field that does not have contribution by the stirrup as shown in Fig. 8 is assumed. Shear strength ${}_{cf}Q_{Su,a}$ of the arch mechanism is shown by Equation. (1).

$${}_{cf}Q_{Su,a} = \sigma_a \cdot b \cdot D \cdot \tan\theta \big/ 2 \qquad (1)$$

where

σ_a : compressive stress of arch mechanism
b : width

D : depth

θ : angle of arch strut ($\tan\theta = \sqrt{(L_0/D)^2+1} - (L_0/D)$)

L_0 : clear span

As carbon fiber sheets do not completely enclose top and bottom longitudinal bars, the stress of the truss struts cannot be directly transferred from top bars to bottom bars. Therefore, a new truss mechanism as shown in Fig. 7 is proposed in this paper. The truss model has the characteristic that stress field composes of two regions. In each region, stress is uniformly distributed, and the angle of the truss strut is constant. However, the angle ϕ_1 of the truss strut in Region 1 is smaller than ϕ_2 in Region 2, so the truss strut is bent on the anchoring line. Then, the using assumption is that the main reinforcement are strong infinitely and the axial force of the anchoring plate is zero. Investigating results of tests, the angle of the truss strut in Region 2 is 45 degrees and a tensile stress of carbon fiber sheets is 1,800N/mm^2. From these assumptions, shear strength of truss mechanism is shown in Equation (2).

$${}_{cf}Q_{Su,t} = b\cdot j_t\cdot\sum\left(p_w\cdot\sigma_{wy}\right)\cdot\cot\phi_2 \qquad (2)$$

where

j_t :the distance from top bar to bottom bar
$\Sigma(p_w\ \sigma_{wy}) = {}_sp_w\ {}_s\sigma_{wy} + {}_{cf}p_w\ {}_{cf}\sigma_{wy}$
${}_sp_w$: ratio of existing stirrup
${}_{cf}p_w$: ratio of transverse reinforcement of carbon fiber sheet
${}_s\sigma_{wy}$: yielding stress of existing stirrup
${}_{cf}\sigma_{wy}$: tensile stress of carbon fiber (1,800 N/mm^2)
ϕ_2 : angle of truss strut in Region 2 ($\cot\phi_2=1$)

As the proposed truss mechanism consists of two regions, there are two compressive stresses of truss struts. From the following reason, the compressive stress of the truss strut in Region 2 is employed for that of condition (C). The first reason is that it is difficult for the truss strut in Region 2 to break later than the one in Region 1, which is composed of the slab or confined by anchoring plates. The second reason is that sliding failure in Region 1, which is described in the following section, is considered to be dominant. Therefore, shear strength ${}_{cf}Q_{Su}$ of a retrofitted beam is obtained by Equation (3), adding Equation (1) to Equation (2).

$${}_{cf}Q_{Su}\quad b\cdot j_t\cdot\sum\left(p_w\cdot\sigma_{wy}\right) + 0.5\cdot\left(1-\beta_{Su}\right)\cdot b\cdot D\cdot\nu\cdot\sigma_B\cdot\tan\theta \qquad (3)$$

where

$$\beta_{Su} = \frac{2\cdot\sum\left(p_w\cdot\sigma_{wy}\right)}{\nu\cdot\sigma_B}$$

$$\nu = 0.7 - \sigma_B/196$$

σ_B : strength of concrete (N/mm^2)

Bond strength:

The bond strength is estimated, considering the transverse reinforcement of carbon fiber sheets, using the same macroscopic model and the same condition as shear strength estimation. The bond strength is derived from the limitation of the truss mechanism that is restricted by bond stress of longitudinal bars. Therefore, bond strength ${}_{cf}Q_{Bu,t}$ of the truss mechanism is expressed by Equation (4). The ultimate bond stress a unit area (τ_{Bu}) refers to ref [5].

$${}_{cf}Q_{Bu,t} = \tau_{Bu}\cdot j_t\cdot\sum\Phi \qquad (4)$$

where

$\Sigma\Phi$: sum of a circumference of longitudinal bars

τ_{Bu} : ultimate bond stress

Equations (5) and (6) show then stresses σ_t and σ_a of truss and arch struts, respectively. Equation (7) is derived from the stress σ_a and the proposed model.

$$\sigma_t = {2\cdot\tau_{Bu}\cdot\Sigma\Phi} \Big/ {b\cdot\sin^2\phi_2} \tag{5}$$

$$\sigma_a = \nu\cdot\sigma_B - \sigma_t \tag{6}$$

$$_{cf}Q_{Bu,a} = 0.5\cdot\left(\nu\cdot\text{ƒ Ð}_B - {2\cdot\tau_{Bu}\cdot\Sigma\Phi} \Big/ {b\cdot\sin^2\phi_2}\right)\cdot b\cdot D\cdot\tan\text{ƒ ⁄} \tag{7}$$

Assumed that the stress transfer mechanism is same as the mechanism for estimating shear strength, the angle ϕ_2 of truss struts in Region 2 is 45 degrees. Therefore, bond strength $_{cf}Q_{Bu}$ of a retrofitted beam is obtained by Equation (8), adding Equation (4) to Equation (7).

$$_{cf}Q_{Bu} = \text{ƒ Ñ}_{Bu}\cdot j_t\cdot\Sigma\Phi\{\,0.5\cdot(1\,|\,\text{ƒ À}_{Bu})\cdot b\cdot D\cdot\text{ƒ Ëƒ Ð}_B\cdot\tan\text{ƒ ⁄} \tag{8}$$

where

$$\beta_{Bu} = \frac{2\cdot\tau_{Bu}\cdot\Sigma\Phi}{b\cdot\nu\cdot\sigma_B}$$

The bond strength is calculated, assuming bond failure of bottom bars. This corresponds to the assumption that the bond failure at the top bars does not occur earlier than that at the bottom bars. In general, bond stress of top bars is larger than that of bottom bars. Since a usual beam has the slab, bond splitting line become longer than that of a beam without slab. Besides, in the case of strengthening beams using carbon fiber sheet, it locates most outside. So cover concrete is confined by carbon fiber, and the decrease of the strength is not distinct. Then it is considered that the merit compensates the defect adequately. It is noted that members in old buildings to be retrofitted have so small amount of longitudinal reinforcement that the members do not fail in bond.

Sliding strength:

Sliding failure as shown in Fig. 7 occurred on the boundary between slab and beam. This failure mode is also discusses elsewhere [ref. 2]. First, cracks occurred on the boundary of slab paralleled to axial of member. Next, the cracks propagated like cracks of direct shear failure. And, the beam is separated from slab gradually. This boundary portion is considered to be critical section because of poor transverse reinforcement of the original sturrups. Consequently shear stress of the boundary has an upper limit. Judging from such a failure pattern, shear stress τ_1 of Region 1 seems to be restricted under the same stress field as calculating shear strength. The limit shear stress is assumed to be expressed by Birkland's formula [4]. Applying this formula to beams, contribution of normal stress is equal to zero. As a result, the sliding stress τ_{Sp} is expressed by Equation (9).

$$\tau_{Sp} = 2.78\text{¥}\sqrt{_s p_w \text{¥}_s\,\sigma_{wy}} \tag{9}$$

where

τ_{Sp} : sliding stress (N/mm^2)
$_sp_w$: ratio of existing stirrup
$_s\sigma_{wy}$: yielding stress of stirrup

Assuming that shear stress τ_1 of Region 1 is limited to Birkland's formula, shear stress τ_2 of Region 2 is also restricted by equilibrium. As shear stress τ_1 of Region 1 is equal to shear stress τ_2 of Region 2 under the proposed macroscopic model, shear stress τ_2 of Region 2 equals sliding stress τ_{Sp}. The angle of the truss strut in Region 2 is assumed to be 45 degrees the same as the shear strength calculation. As is the case with sliding strength, truss stress in Region 2 is transmitted by 45 degrees. In other words, $\cot\varphi_2$ equals 1. As like estimating shear strength, sliding strength ${}_{cf}Q_{Sp,t}$ of the truss mechanism and sliding strength ${}_{cf}Q_{Sp,a}$ of the arch mechanism is shown by Equations (10) and (11). Therefore, sliding strength is obtained by Equation (12).

$$ {}_{cf}Q_{Sp,t} = b \cdot j_t \cdot \tau_{Sp} \tag{10} $$

$$ {}_{cf}Q_{Sp,a} = 0.5 \cdot \left(\nu \cdot \sigma_B - 2 \cdot \tau_{Sp}\right) \cdot b \cdot D \cdot \tan\alpha \tag{11} $$

$$ {}_{cf}Q_{Sp} = b \cdot j_t \cdot \tau_{Sp} + 0.5 \cdot \left(1 - \beta_{Sp}\right) \cdot b \cdot D \cdot \nu \cdot \sigma_B \cdot \tan\alpha \tag{12} $$

where

$$ \beta_{Sp} = \frac{2 \cdot \tau_{Sp}}{\nu \cdot \sigma_B} $$

Design of anchorage:

The principle of the anchoring design is to prevent anchoring failure prior to fracturing of carbon fiber sheets. For that purpose, the anchoring part must resist the tensile stress from carbon fibers. The anchoring bolts and the plates are determined so that shear yielding strength of bolt, bearing failure of concrete, and yielding of plates do not occur. Fig.9 shows a model to calculate design force for the anchoring portion. Especially care is required for the design shear force of the bolt that the value obtained from the model diagram should be doubled. Though the model diagram shows one span, actually the anchoring bolt is loaded from adjacent sides.

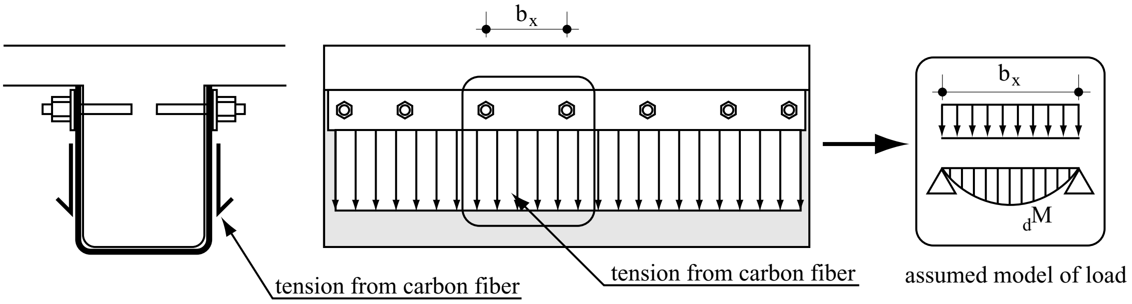

Fig.9 Model for the design of anchorage

EVALUATION EACH STRENGTH

Fig.10 shows correspondence of the experimental and computed values of shear strength. The vertical axis in Fig.10 indicates non-dimensional test values that is ratio of experimental strength to calculated flexural strength by equation (13). The horizontal axis indicates non-dimensional shear strength that is ratio of calculated shear strength to calculated flexural strength. Triangular symbols in Fig.10 are located in the region of danger-side evaluation. However, these are the cases that carbon fiber sheets without anchors were peeled off. In these cases, specimens failed in shear without using a high potential strength of carbon fiber sheet. So, these cases are out of applicable range of the proposed shear strength evaluation. The other plots in the danger-side of Fig.10 are corresponding to the specimens for which sliding failure was observed. So, they should be evaluated by other formula that is proposed for sliding strength. Fig.11 shows correspondence of the sliding strength for evaluation. Though only a few test dates are available, the proposed sliding strength is demonstrated by Equation (12).

$$ Q_{Mu} = {}^{M_u}\!/_{L_o} = \frac{0.9 \cdot a_t \cdot \sigma_y \cdot d}{L_o} \tag{13} $$

where

M_u : flexural strength
A_t : cross sectional area of longitudinal bar
σ_y : yielding stress of longitudinal bat
d : effective depth

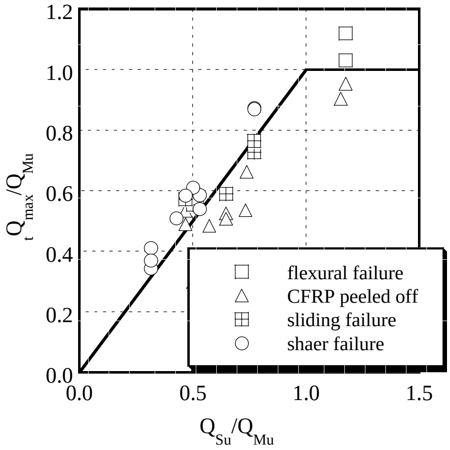

Fig. 10 correspondence of the experiment value and the computation value of shear strength

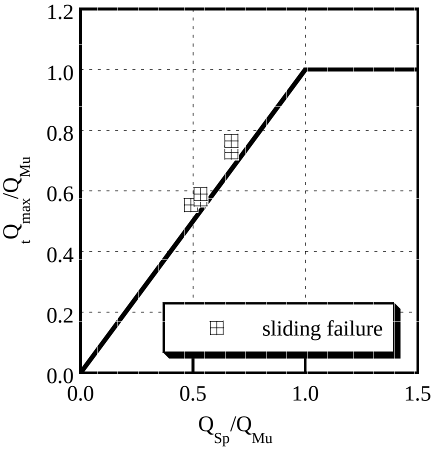

Fig. 11 correspondence of the experiment value and the computation value of sliding strength

CONCLUSIONS

The conclusions of this paper are as follows:

1. As if carbon fiber sheets do not enclose top and bottom bars, the sufficient strengthening effectiveness is observed for wrapping carbon fiber sheets with side-anchoring in experiment.
2. The accuracy of the proposed equations of this side-anchoring technique is demonstrated through comparisons of calculated and experimental strengths.
3. Design equations and procedures are proposed for shear, bond, sliding failures and for anchoring of carbon fiber sheets.

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