EVALUATION METHOD FOR SHEAR CAPACITY OF RC MEMBERS RETROFITTED WITH EXTERNALLY BONDED CONTINUOUS FIBER SHEET

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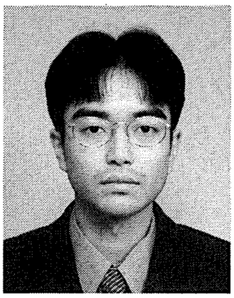

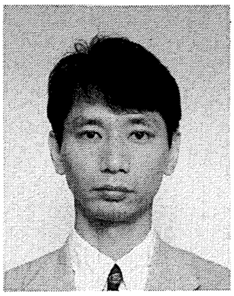

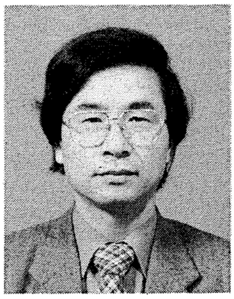

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This paper describes an evaluation method for the shear capacity of RC members retrofitted with externally bonded continuous fiber (CF) sheets. The proposed method is based on coupled mechanical models. A simplified model calculates the opening of major diagonal cracks. A constitutive model of the interfacial zone between CF sheet and concrete then calculates the bonding and debonding behavior of the CF sheet. Since the evaluation is based on realistic mechanical assumptions, it can automatically distinguish between member failure models: "Compression shear failure" and "CF sheet rupture". The accuracy and applicability of the proposed method is verified using experimental data taken from the literature. It is demonstrated that the method is able to predict the shear capacity of members with higher accuracy then the equation used in the current design procedure.

Keywords: CF sheet, retrofit, RC member, shear capacity, shear contribution, boding, debonding

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1. INTRODUCTION

There are a number of specifications for the repair or strengthening of reinforced concrete structures using continuous fiber sheet in Japan. References 1 and 2 recommend estimating the shear capacity of the strengthened structures as follows:

$$V_{cf} = k \cdot \{A_{cf} \cdot f_{cf} \cdot (\sin\theta + \cos\theta)/s_{cf}\} \cdot z \tag{1}$$

Where, k is the effective modification coefficient for the tensile strength of continuous fiber sheet, A_{cf} is the unit area of the continuous fiber sheet, f_{cf} is the tensile strength of the continuous fiber sheet, and s_{cf} is the unit width of the continuous fiber sheet inclined at angle θ degrees. Coefficient k is equal to 0.8 for carbon fiber and 0.4 for aramid fiber sheet. The ultimate shear capacity is predicted on the basis of a truss analogy. Most specification in Japan recommended making estimated by multiplying by coefficient k. This design method is adequate for actual design work. However, coefficient k does not take into account the type of continuous fiber or the amount of sheet reinforcement because it is empirical.

A number of coefficients have been developed that account for sheet type. However, there remains a need for a new design procedure that is not only free of empirical limitations, but is also based on the actual elastic modulus of the sheet and type of structural member. To develop such a procedure, actual behavior under the influence of a shear force must be taken into account.

To evaluate the shear force carried by a continuous fiber sheet more rationally, it is necessary to understand bonding and delaminating behavior of continuous fiber sheet and concrete, as pointed out by Uji and Triantafillow [4][5]. The authors have previously proposed a numerical method for estimating this bonding and delaminating behavior, and have also developed a derivation of the constitutive models for numerical calculations. This paper focuses on developing a design method for ultimate shear capacity for retrofitted structural members; the proposed method adopts the numerical methods in Reference 7.

2. OUTLINE OF PROPOSED METHOD

In retrofitted structural member, a sheet covering a major diagonal crack will delaminate as the crack opens. The tensile force carried by the continuous fiber sheet is evaluated thorough stress analysis, enabling calculation of the delamination length and the crack width.

The calculation procedure for the proposed method is summarized in Fig. 1. The ultimate shear capacity as used in this method is based on the truss analogy. The shear force carried by the web reinforcement are both calculated by the truss equation [8][9]. The shear force carried by the sheet is calculated by first calculating the delamination process in each divided element of the retrofitted structural member by stress analysis., then obtaining the shear force from calculated ultimate strain of the sheet. In a case where sheet strips are affixed, as shown in Fig. 2, the divided number is determined from the product of bonding width and strip spacing. The major diagonal crack width and delamination process of the sheet are determined using the rigid model and the bond constitutive model, respectively. The proposed method includes calculation procedures for predicting whether the failure mode is shear compression failure or sheet rupture.

3. CALCULATION METHOD

3.1 Shear force carried by the sheet

The shear force carried by the concrete, V_c, is calculated as follows [8]:

$$V_c = 0.2(f_c' \cdot p_t)^{1/3} (d/1000)^{-1/4} [(0.75 + 1.4/(a/d)] \cdot b_w \cdot d \tag{2}$$

Where, f_c' is the compressive strength of concrete [N/mm^2], p_t is the longitudinal reinforcement ratio [%], d is the effective depth [mm], a is the shear span [mm], and b_w is the width of the member web. In the proposed

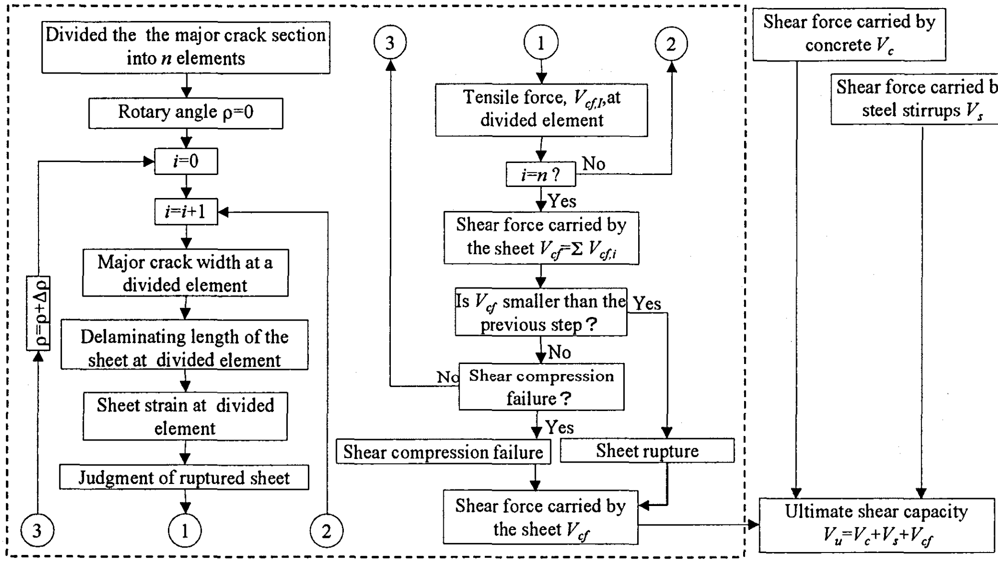


Fig. 1 Calculation flow of the proposed method

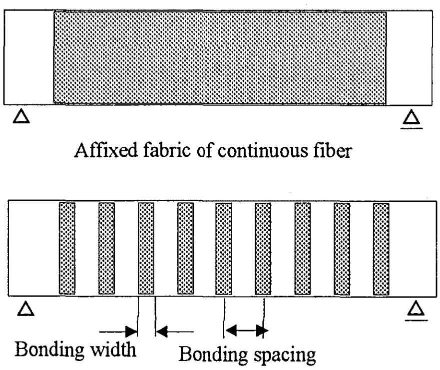


Fig.2 Retrofitting methods

method, any sheet affixed to the underside of the specimen does not contribute to the flexural reinforcement. This is because the underside sheet may not contribute to the shear force carried by the concrete.

Assuming that the shear steel stirrups have reached their yield strength, the shear force carried by the stirrups is calculated as follows:

$$V_s = A_w \cdot f_{wy}(\sin\alpha + \cos\alpha) \cdot (z/s_s) \tag{3}$$

Where, A_w is the cross-sectional area of stirrups per spacing s_s, f_{wy} is the yield strength of the stirrups, α_s is the angle of stirrup and its longitudinal direction, z is the moment arm (usually taken as $d/1.15$), and s_s is the vertical spacing of the stirrups.

The steel stirrups may not reach their yield strength if the retrofitted member has large amount of sheet reinforcement. However, the proposed method considers the large deflection that occurs with the opening of the diagonal crack, so the assumption is valid.

3.2 Shear force carried by continuous fiber sheet

a) rigid model

It is very difficult to calculate the behavior of the major diagonal crack under shear force using a rigorous procedure. In the existing design method, crack width is calculated as a function of the stirrup strain [10]. This formula, however, is suitable for estimating the crack width only when the ultimate shear capacity of the member is given. Also, the formula was designed to provide control over the occurrence of the diagonal crack. Consequently, it is not suitable for use in the prediction shear capacity.

In this study, the diagonal crack width will be estimated using a simplification of Walther's model [11][12], in which it is assumed that concrete is a rigid body. Deformation of the member after shear cracking is represented by rotation of the member. (See Fig. 3)

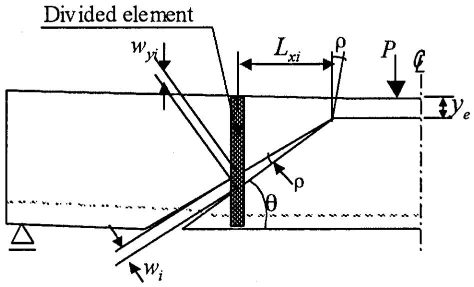


Fig. 3 Rigid body model

Deformation of the shear compressive zone, S_0, is calculated as follows [10]:

$$S_0 = y_e \cdot \rho = \varepsilon_b \cdot d\sqrt{y_e / d} \qquad (4)$$

Where, y_e is the vertical depth from top of beam to tip of shear crack, ρ is the rotational angle of the shear crack, and ε_b is the strain of the shear compressive zone. The crack width of each divided element, w_i, is defined as a function of the angle, ρ, as,

$$w_i = \frac{\rho \cdot L_{xi}}{\cos\theta} \qquad (5)$$

Where $L_{x,i}$ is the horizontal distance from the tip of the shear crack to each divided element and θ is the angle between the longitudinal axis of the member and the shear crack.

The crack width in the vertical direction, $w_{y,i}$, is obtained as the cosine of crack width, w_i:

$$w_{y,i} = \rho \cdot L_{x,i} \qquad (6)$$

Experimental observations have shown that angle θ is 35 degrees [13]. The author have conducted a parametric study using the proposed method. On the basis of the above discussion, depth y_e is equal to ten percent of the effective depth. These parameters may change under the influence of various factor such as the shape of the member and the arrangement of reinforcing bars. In this study, the parameters are not influenced by such variations; this issue will be discussed in a future work.

The proposed method will be verified only with respect to the structural member being subjected to a concentrated load; the location of the shear crack does not have to be given. Application of the proposed method to a uniformly loaded member would require that the location of the crack be given. Again, this issue will be clarified in a future work.

b) Constitutive model for bond between continuous fiber sheet and concrete

The authors proposed derivation methods for the constitutive model, including bilinear and cut-off models, and discussed the applicability of these models in Reference 6. The bilinear model, namely an elasto-softening-delamination model, is suitable for rigorous numerical analysis. On the other hand, a cut-off model, or elasto-delamination model, is very easily derived as a simplification of the bilinear model: the fracture energy I simply made the same as in the bilinear model. These models are shown in Fig. 4.

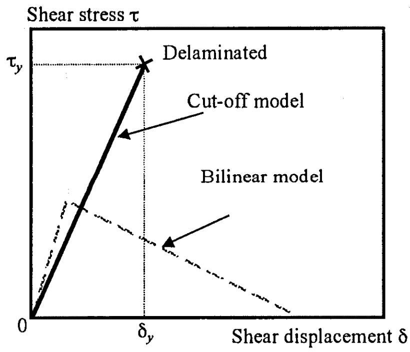


Fig. 4 Constitutive models

The sensitivity analysis carried out in Reference 6 demonstrated that simplified analysis based on the cur-off model dives similar results to the rigorous procedure using the more complex bilinear model. (See appendix) Based on this finding, the cut-off model was adopted in the proposed method.

For the cut-off model shown in Fig. 4, the relationships is,

$$\tau = \frac{\tau_y}{\delta_y}\delta \quad (0 \le \delta \le \delta_y) \tag{7}$$

Where the stress, τ_y, and displacement. δ_y, are both material parameters of the constitutive model. The main factor influencing bonding and delamination of the continuous fiber sheet is the elastic modulus of the epoxy resin. (See Reference 6) The stress, τ_y, and displacement, δ_y, take values of 7.5 [N/mm^2], and 0.2 [mm], respectively, when the continuous fiber sheet is affixed using a resin with a normal elastic modulus. These figures do not depend on the type of continuous fiber sheet.

c) Stress analysis of each divided element

The calculation procedure is schematically summarized in Fig. 5. The state of the bonding and delamination in the divided element shown in Fig. 6 is defined as follows:

$$\ell_{u,i} = \ell_{ub,i} + \ell_{up,i} \tag{8}$$

$$\ell_{d,i} = \ell_{db,i} + \ell_{dp,i} \tag{9}$$

$$h = \ell_{u,i} + \ell_{d,i} \tag{10}$$

Where. $\ell_{u,i}$ and $\ell_{d,i}$ are the distances to the top and bottom of the element from the shear crack point, respectively, $\ell_{ub,i}$ and $\ell_{db,i}$ are the bonding lengths upward and downward from the shear crack point, respectively, and $\ell_{up,i}$ and $\ell_{dp,i}$ are the delamination lengths upward and downward from the shear crack point, respectively.

It is assumed that the concrete and the continuous fiber sheer are both rigid bodies, since numerical procedures this assumption and that the system is in equilibrium, the fundamental equations for the displacement of the continuous fiber sheet are,

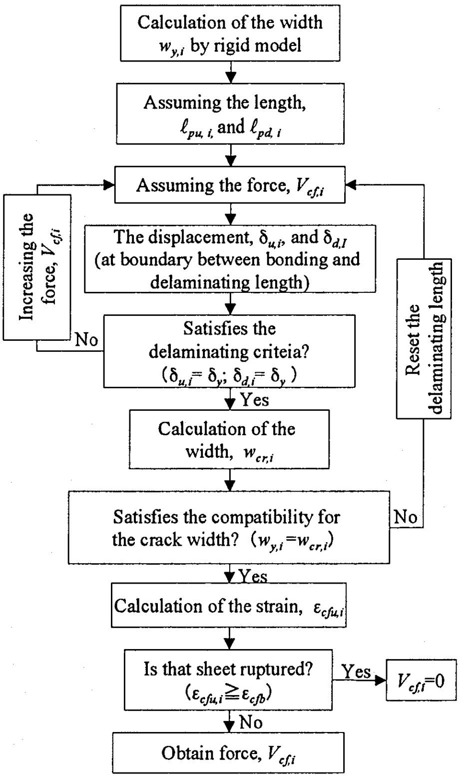


Fig. 5 Calculation procedure for stress analysis

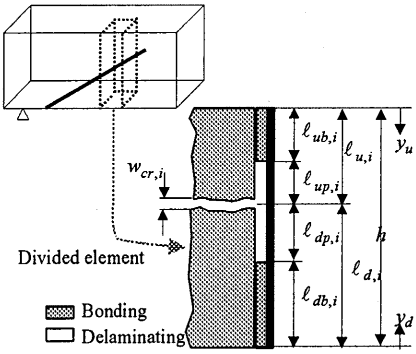


Fig. 6 Bonding and delaminating states at divided element

$$E_{cf}\cdot t_{cf}\frac{d^2u_{cf}(y_u)}{dy_u}-\frac{\tau_y}{\delta_y}u_{cf}(y_u)=0 \quad (0\le y_u\le \ell_{ub,i}) \tag{11}$$

$$E_{cf}\cdot t_{cf}\frac{d^2u_{cf}(y_d)}{dy_d}-\frac{\tau_y}{\delta_y}u_{cf}(y_d)=0 \quad (0\le y_d\le \ell_{db,i}) \tag{12}$$

Where, E_{cf} is the elastic modulus of the continuous fiber sheet, t_{cf} is the total thickness of the bonded sheet, and $u_{cf}(y_u)$ and $u_{cf}(y_d)$ are the displacements of the continuous fiber sheet at upper and lower elements, respectively.

Some researchers have reported that if the bonded sheet is not anchored at the top or bottom end of the structural member, a retrofitted member will exhibit inferior strengthening [3]. Considering this, the boundary conditions are set as follows:

$$\begin{aligned} &y_u=0; u_{cf}(y_u)=0\\ &y_d=0; u_{cf}(y_d)=0\\ &y_u=\ell_{ub,i}; \sigma_{cf}(y_u)=V_{cf,i}/A_{cf,i}\\ &y_u=\ell_{db,i}; \sigma_{cf}(y_d)=V_{cf,i}/A_{cf,i}\end{aligned} \tag{13}$$

Where, $V_{cf,i}$ is the tensile force at a divided element, $A_{cf,i}$ is the cross-sectional area of continuous fiber sheet at a divided element, and σ_{cf} is the stress on the continuous fiber sheet. Displacement of the continuous fiber sheet are obtained by solving Equation (11) and (12) with the boundary conditions defined in Equation (13).
In a divided element, the crack, $w_{cr,i}$ including elongation of the sheet, and shear displacement at boundary between bonding and delamination zone, is calculated by

$$w_{cr,i} = \frac{V_{cf,i}}{E_{cf} \cdot A_{cf,i}}(\ell_{up,i} + \ell_{dp,i}) + u_{cf}(\ell_{ub,i}) + u_{cf}(\ell_{dp,i}) \quad (14)$$

where $u_{cf}(\ell_{ub,i})$, and $u_{cf}(\ell_{db,i})$ are the displacement at the boundary.

Iterative computation is required to obtain the correct number in this analysis. The convergence condition is that the crack width, $w_{cr,i}$, is equal to the crack width, w_{yi}, calculated from Equation (6). If this condition is satisfied, we are able to obtain correct figures for delamination length and tension force in a divided element.

d) Shear force carried by continuous fiber sheet

The strain of the continuous fiber sheet in each element is obtained from the calculated delamination length, $(\ell_{up,i} + \ell_{dp,i})$, and crack width, $w_{y,i}$, as follows:

$$\varepsilon_{cfu,i} = \frac{w_{y,i} - \delta_b}{\ell_{uo,i} + \ell_{dp,i}} \quad (0 \le \varepsilon_{cfu,i} < \varepsilon_{cfb}) \quad (15)$$

Where, ε_{cfb} is the ultimate strain of the sheet. If strain $\varepsilon_{cf,i}$ is equal to or greater than the ultimate strain, the tensile force in the divided element should be taken as zero because this indicate rupture of the sheet within the element. The ultimate shear force carried by the sheet is calculated as follows:

$$V_{cf} = \sum_{i=1}^{n} V_{cf,i} \quad (16)$$

e) Judgment of failure mode

There are two possible failure modes for retrofitted members subjected to a shear force, as follows:

- Sheet rupture: the affixed sheet ruptures as the shear crack opens, leading to a reduction in the shear force carried by the sheet;
- Shear compression failure: the strain of the compressive zone reaches the compressive failure criteria, but the sheet does not rupture.

These failure modes are illustrated in Fig. 7. The above calculation method for shear force carried by the sheet is effective for the sheet rupture mode. In the case of shear compression failure, the following method is used to judge failure of the shear compression zone.

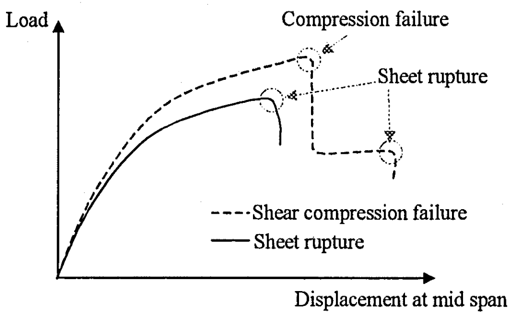


Fig. 7 Types of failure mode

From Equation (4), the relationship between the strain of the compression zone, ε_b, and the rotation angle, ρ, is as follows:

$$\varepsilon_b = \frac{y_e \cdot \rho}{d\sqrt{y_e / d}} = \rho\sqrt{y_e / d} \quad (17)$$

The strain, ε_b, is taken as 0.0025 on the basis of a parametric study conducted by the authors [7].

Several relationships between rotation angle shear force carried by the sheet, based on the proposed method, are shown in Fig. 8. The calculation conditions are summarized in Table 1. When the affixed sheet ruptures, the shear force falls (see Case 3 and Case 4). That means that the failure mode is sheet rupture. In this failure mode, the ultimate shear force is the peak value (see point (a) in Fig. 8). On the other hand, in the case of shear compression failure, the ultimate shear force is the value when the strain, ε_b, reaches the failure criteria (see point (b) in Fig. 8).

Table 1 Calculating condition

	Continuous fiber sheet				Concrete member		
	Elastic modulus (GPa)	Tensile strength (MPa)	Thickness (mm)	Ultimate strain (μ)	Effective depth (mm)	Overall depth (mm)	Shear to span ratio
case1	245	3670	0.0556	14900	300	350	3
case2	245	3670	0.1086	14900			
case3	433	2510	0.0556	5790			
case4	433	2510	0.1086	5790			

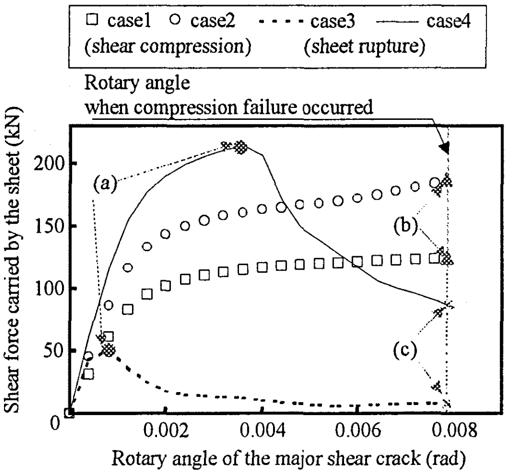


Fig. 8 The relationships between the rotary angle and the shear force

3.3 Ultimate shear capacity

The ultimate shear capacity of a retrofitted structural member is predicted as follows:

$$V_u = V_c + V_s + V_{cf} \tag{18}$$

4. VERIFICATION OF PROPOSED METHOD

4.1 Data selection

Experimental data obtained by other researchers is summarized in Table 2 [14][15][16][17][18][19]. The authors selected this data on the basis of the experiments providing sufficient anchoring of the affixed sheet at both ends of the structural member; this means that fixed ends can be adopted as boundary conditions for the stress analysis. The failure mode is classified as "N/A" if the mode was not specified in the original paper.

Table 2 Experimental data [14][15][16][17][18][19]

Authors	Concrete member					Continuous fiber sheet				Failure mode*		Ultimate capacity	
	Effective depth (mm)	Shear to span ratio	Main reinforcement ratio (%)	Compressive strength of concrete	With or without steel stirrups	Type	Elastic modulus (GPa)	Tensile strength (MPa)	Thickness (mm)	Observed	Predicted	Observed	Predicted**
Kato et al. [14]	200	1.5	1.98	38.2	With	Carbon	227	3870	0.056	N/A	C	149	128
	200	1.5	1.98	38.2	W/O	Carbon	227	3870	0.056	N/A	C	146	128
	200	1.5	1.98	38.2	With	Carbon	227	3870	0.056	N/A	R	129	126
Kato et al. [15]	200	2	2.76	30.4	W/O	Carbon	433	2510	0.054	R	C	75	61
	200	2	2.76	30.4	W/O	Carbon	433	2510	0.054	R	C	86	87
	200	2	2.76	30.4	With	Carbon	433	2510	0.054	R	C	92	84
	200	2	2.76	30.4	W/O	Carbon	433	2510	0.109	R	C	93	91
	200	2	2.76	30.4	W/O	Carbon	245	3670	0.109	C	C	285	243
	200	2	2.76	30.4	W/O	Carbon	245	3670	0.056	C	C	236	213
	200	2	2.76	30.4	With	Carbon	433	2510	0.056	R	C	569	416
	200	2	2.76	30.4	W/O	Carbon	433	2510	0.109	C	C	530	370
Miyauchi te al. [16]	165	3	4.91	35.8	W/O	Carbon	230	3480	0.111	N/A	C	166	140
	165	3	4.91	35.8	W/O	Carbon	230	3480	0.111	N/A	R	156	88
	165	2.7	4.91	35.8	With	Carbon	230	3480	0.111	N/A	R	162	196
	165	2	3.75	35.8	W/O	Carbon	230	3480	0.111	N/A	C	202	184
Umezu et al. [17]	253	3	2.19	42	W/O	Aramid	73	2700	0.044	N/A	C	146	140
	253	3	2.19	42	W/O	Aramid	73	2700	0.044	N/A	R	180	196
	253	3	2.19	42	W/O	Aramid	73	2700	0.088	C	C	110	110
	253	3	2.19	42	W/O	Aramid	73	2700	0.088	C	C	173	169
	253	3	2.19	42	W/O	Aramid	73	2700	0.144	C	C	209	190
	253	3	2.19	42	W/O	Aramid	73	2700	0.144	C	C	224	190
	399	3	2.24	42	W/O	Aramid	73	2700	0.144	C	C	254	210
	499	3	2.05	42	W/O	Aramid	73	2700	0.144	C	C	424	328
	499	3	2.05	42	W/O	Aramid	73	2700	0.288	C	C	379	391
Takada et al. [18]	400	2.5	2.28	34	W/O	Carbon	240	3480	0.111	R	C	569	524
	400	2.5	2.28	34	W/O	Aramid	90	2700	0.169	C	C	662	604
	600	2.5	1.43	34	W/O	Carbon	240	3480	0.111	N/A	C	145	119
	600	2.5	1.43	34	W/O	Aramid	90	2700	0.169	N/A	C	140	108
Higashino et al. [19]	200	2	2.76	32	W/O	Aramid	108	2060	0.069	N/A	C	177	146
	200	2	2.76	32	W/O	Aramid	72	2060	0.069	N/A	C	176	129
	200	2	2.76	32	W/O	Aramid	108	2060	0.138	N/A	C	179	144
	200	2	2.76	32	W/O	Aramid	72	2060	0.139	N/A	C	176	133
	200	2	2.76	32	With	Aramid	108	2060	0.069	N/A	C	203	171
	200	2	2.76	32	With	Aramid	72	2060	0.069	N/A	C	200	154
	200	2	2.76	32	With	Aramid	108	2060	0.138	N/A	R	202	222
	200	2	2.76	32	With	Aramid	72	2060	0.139	N/A	R	166	114
	200	2	2.76	32	With	Carbon	433	2510	0.109	N/A	R	166	114

*: C means shear compression failure, R means sheet rupture **: The calculation result based on the divided number is equal to twenty

4.2 Applicability

Figure 9 compares the predicted ultimate shear capacity based on the proposed method with the observed values. The proposed method is shown to be capable of predicting the ultimate shear capacity of these retrofitted members. The accuracy of this prediction remains good even where the failure mode is wrongly diagnosed, though the expectation was that accuracy would deteriorate if an incorrect failure mode was predicted. The reason for this cannot be clarified in this study, since not only the accuracy of the proposed method but also the predictive ability of the truss analogy comes into question.

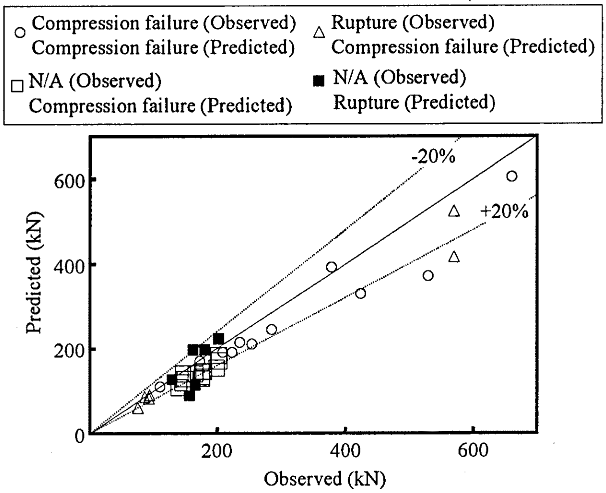


Fig. 9 Calculation result of the proposed method

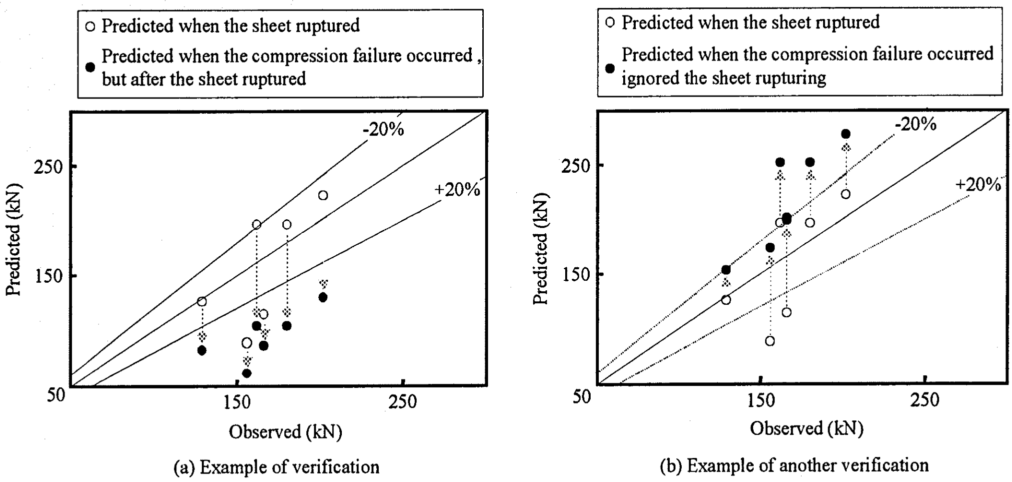
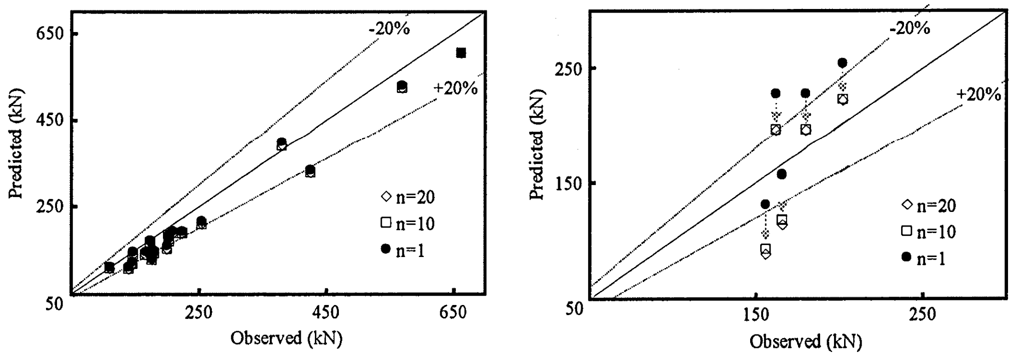


Fig. 10 Effectiveness of failure mode

The effectiveness of failure mode judgments using the proposed method is now discussed. First, the data for sheet rupture are selected. Figure 10 shows the predicted shear force carried by the sheet when the compression zone fails are overestimated in cases where the sheet ruptures. Further, predictions of shear force when the compression zone fails but the sheet does not rupture are underestimated at higher stress, because the failure criterion of the sheet is ignored. These results indicate that the failure mode has a great influence on the accuracy of the predicted shear force carried by the sheet.

4.3 Number of elements

Figure 11 compares predictions made with different numbers of elements with the observations. Results for a predicted failure mode of sheet rupture are shown in Fig. 11(a), and those for a failure mode of shear compression failure are shown in Fig. 11(b). Element numbers are 1, 10, and 20. Accuracy is affected by this number when the prediction was sheet rupture. This is because the estimation of delamination length in the stress analysis loses accuracy if the divisor is less than 10. The authors recommend that the number of element be at least 10 number when using the proposed method so as to ensure sufficient accuracy.



(a) Shear compression failure (b) Sheet rupture

Fig. 11 Result based on changing the divided number

4.4 Proposed method vs. existing procedure

Figure 12 compares the prediction accuracy of the proposed method with that of the design procedure referenced in Equation (1). The average capacity ratios and the variables are summarized in Table 3. (Capacity ratio means the product of the predicted shear force and the observed value.) The proposed method offers good accuracy compared with the existing design procedure. The authors wish to emphasize that the proposed method is a design procedure that is free of empirical limitations, yet is capable of predicting the ultimate shear capacity more rationally.

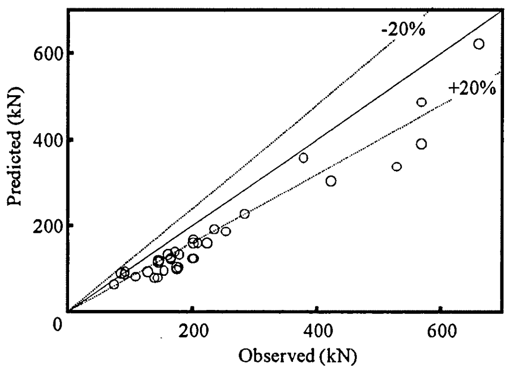


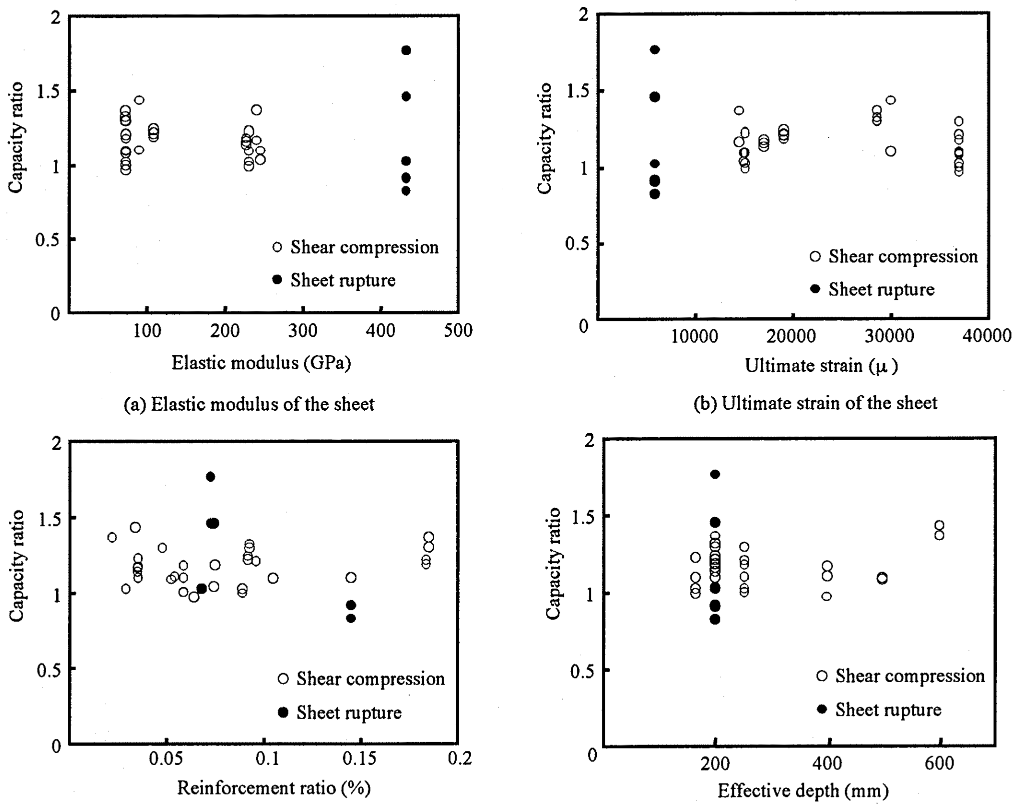
Fig. 12 Calculation result by existing design procedure

Table 3 Comparison of accuracy

	Average capacity ratio	Variable (%)
The proposed method	1.18	15.3
Design procedure (Eq.(1))	1.38	17.2

4.5 Sensitivity

Figure 13 shows the relationship between capacity ratio and factors influencing the prediction of shear capacity. These factors include the elastic modulus of the continuous fiber sheet, the ultimate strain of the sheet, the reinforcement ratio of the sheet, and the effective depth. The reinforcement ratio, ρ_{cf}, is defined as follows:



(a) Elastic modulus of the sheet

(b) Ultimate strain of the sheet

(c) Reinforcement ratio of the sheet

(d) Effective depth

Fig. 13 Relationship between capacity ratio and the factor

$$\rho_{cf} = \frac{2t_{cf} \cdot b_{cf}}{b_w \cdot s} \tag{19}$$

Where, b_{cf} is the unit width of the sheet and s is bonding spacing of the sheet.

In fig. 13, the shear capacity is underestimated when the failure mode is judged to be sheet rupture. The capacity ratio, however, does not incline to these factors.

5. CONCLUSION

This study proposes an evaluation method for concrete members retrofitted with continuous fiber sheet. The proposed method predicts the shear force carried by the sheet on the basis of a stress analysis based on a constitutive model of the band between sheet and concrete. The following conclusions can be drawn from this study:

1. The proposed method is able to predict ultimate shear capacity based on a calculation of the major shear crack and the delamination process of the sheet over the crack. It is also able to differentiate between two failure modes: sheet rupture and shear compression failure.
2. The proposed method offers sufficient accuracy if the member is divided into at 10 elements. With less than 10 elements, the accuracy deteriorates when the predicted failure mode is sheet rupture.
3. Compared with the existing design method, which is an empirical procedure, the proposed method offers sufficient accuracy.

It is concluded that the proposed method is suitable for actual strengthening work based on performance design.

Appendix

In this study, the authors used a cut-off model as the constitutive model for stress analysis. Detail of the reasoning behind this are discussed in Reference 6. Figure A1 shows the results of numerical simulation of the bond between continuous fiber sheet and concrete with both the bilinear and the cut-off model. The theoretical and experimental curves agree well once delaminating begins, even using the cut-off model. It should be noted that numerical calculations using the bilinear model are very complicated, because an iterative procedure such as the Newton-Raphson Method is required. However, the cut-off model does nit require such an iterative procedure. As a result the authors conclude that cut-off model is suitable for stress analysis in the proposed method. Thus the important characteristics of the proposed method are accuracy of prediction once delamination begins, and the simplified numerical procedure.

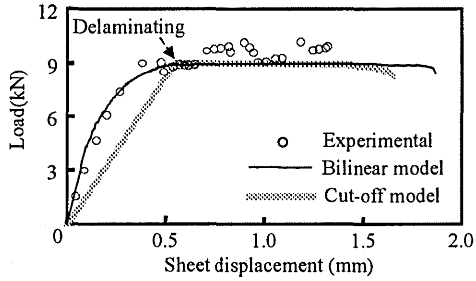


Fig. A1 Simulated result based on bilinear and cut-off model

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