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EVALUATION OF SHEAR CAPACITY OF RC COLUMNS STRENGTHENED BY CONTINUOUS FIBER

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To propose the evaluation method for shear capacity of RC columns strengthened with continuous fiber, stresses of fibers were calculated using previous test data by reverse calculation using the arch-truss method. The total number of test data is 65, including 43 carbon fiber specimens and 22 aramid fiber specimens. It has been reported that these specimens failed without yielding of main bars. The calculated stresses and strains in continuous fibers are related to the reinforcement ratio of the fibers. In this paper, the relationship between reinforcement ratio of fibers and strain energy of fibers is proposed to predict the shear capacity of column specimens. By the proposed method, failure mode of tested specimens, consisting of 52 carbon specimens and 21 aramid specimens with yielding of main bars, is confirmed. The predicted failure types agree with test results in 70% of specimens.

INTRODUCTION

In recent years, the strengthening methods using continuous fibers (sheets, tapes, strands, and others) for reinforced concrete structures are flourishing. Research and development of the strengthening methods to improve the shear capacity and ductility of reinforced concrete members in earthquake resistance has been carried out, and the strengthening effect has been clarified. Till now, experiments on continuous fiber reinforced RC columns had been done by many organizations, and many experiment data are available.

The strength and deformation capacities of continuous fiber reinforced RC columns are often evaluated using expressions meant for ordinary reinforced concrete members. The effects of continuous fiber reinforcements are expressed by substituting fiber stress for steel reinforcements (shear reinforcements) currently. Evaluation of shear capacity based on yield strength is possible for steel reinforcement as steel reinforcements yield with an increasing deformation of a member.

However, in the case of continuous fiber reinforced members, because of the perfectly elastic characteristics of continuous fiber, evaluation of shear capacity on the basis of the failure mechanism, in which member deformation (fiber strain) is considered, is necessary. In this paper, based on previous experimental results, a statistical approach is suggested to evaluate the shear capacity and failure mode of RC members reinforced with continuous fibers.

ANALYSIS METHOD

Data for Analysis

In order to carry out the analysis, a total of 65 column specimens are selected from References 1 to 11. All specimens have a rectangular section without any attaching walls, and were strengthened by continuous fibers. It is reported that all the specimens failed before main bar yielding was observed.

Outline of selected specimens

The specimens included 43 carbon fiber strengthened specimens and 22 aramid fiber strengthened specimens. Structural factors of specimens and the ranges are described below. Figure 1 indicates the distributions of concrete strength, shear span ratio, elastic modulus of fiber and fiber reinforcement ratio, summarized as follows :

(a) Concrete compressive strength $\sigma_B = 16 - 38$MPa
(b) Shear span ratio $M/QD = 1.0 - 2.5$
(c) Axial force $N = 0 - 588$kN
(d) Axial force ratio $\eta = 0 - 0.22$
(e) Elastic modulus of continuous fiber $E_{fme} = 80 - 280$GPa
(f) Hoop ratio (steel reinforcement) $p_{w2} = 0 - 0.30\%$
(g) Fiber reinforcement ratio $p_{wf} = 0.01 - 0.26\%$
(h) Yield strength of hoop $\sigma_{wy} = 320 - 430$MPa
(i) Tensile strength of fiber $\sigma_{fme} = 2200 - 4600$MPa

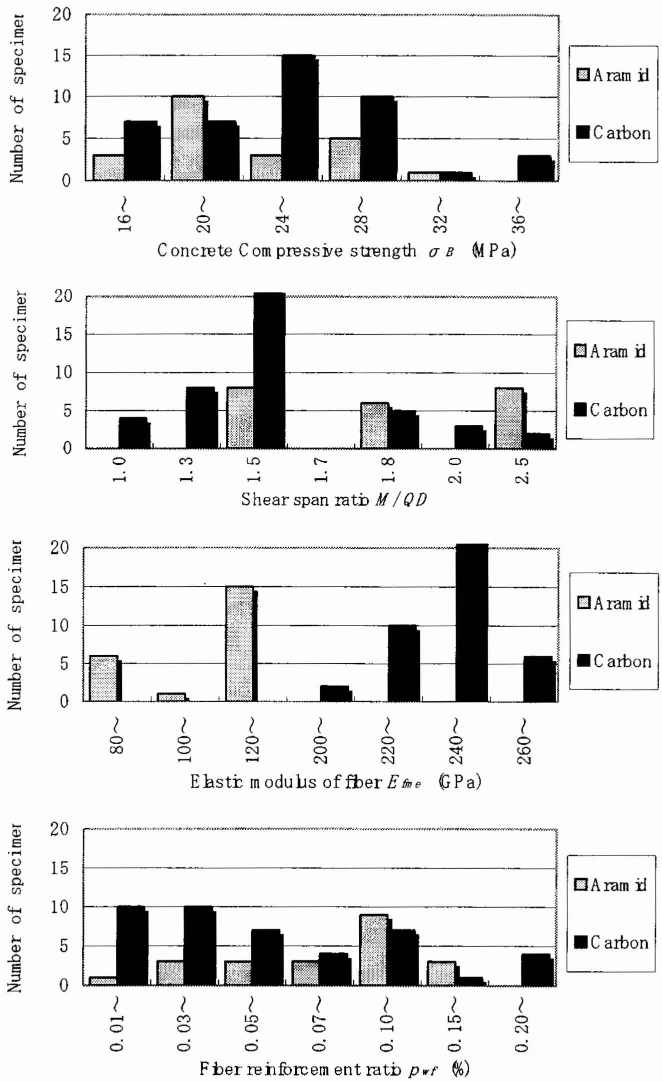

Figure 1. Distributions of structural parameters of selected specimens

Strengthening method of selected specimens

Fiber reinforcements such as sheet, tape or strand type were used for wrapping the column specimens uniformly over the surfaces as shown in

Figure 2. The number of layers of fiber ranged from 1 to 4. There were splice regions of continuous fibers on 0, 1 or 2 surfaces in the perpendicular directions to loading as shown in Figure 2. Epoxy is used for primer, putty and resin for all the specimens.

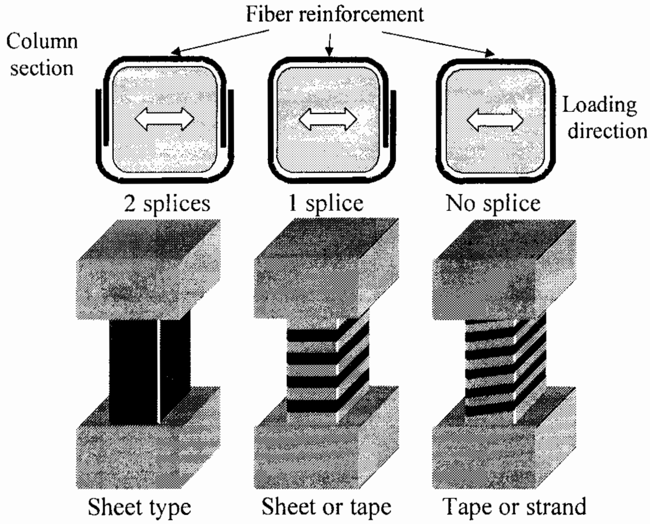

Figure 2. Strengthening method of fiber reinforcement

Loading method of selected specimens

Specimens were loaded under the anti-symmetrical moment (BRI type or Ohno type) or cantilever type, either cyclically or monotonically as shown in Figure 3. The axial force was kept constant for all specimens.

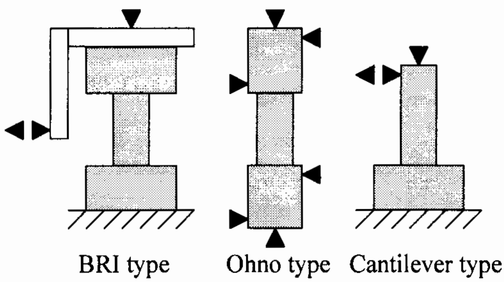

Figure 3. Loading method

Calculation Method for Analysis

The evaluation formula of shear capacity proposed for ordinary steel reinforced concrete members by Architectural Institute of Japan (AIJ)[12] is used for analysis. This formula is based on the summation of arch – truss mechanism. Using this formula, the stress in the continuous fibers is calculated backwards from the observed maximum strength of tested specimens. The formula is :

$$Q_{su} = b \cdot j_t \cdot \sum (p_w \cdot \sigma_w) \cot\phi + \tan\theta \cdot (1-\beta) \cdot b \cdot d \cdot \nu_c \cdot \sigma_B / 2 \quad (1)$$

$$\sum (p_w \cdot \sigma_w) \le \nu_c \cdot \sigma_B / 2 \quad (2)$$

$$\tan\theta = \sqrt{(H/d)^2 + 1} - H/d \quad (3)$$

$$\beta = \left\{(1+\cot^2\phi) \cdot \Sigma(p_w \cdot \sigma_w)\right\} / (\nu_c \cdot \sigma_B) \quad (4)$$

$$\cot\phi = \min\left\{2.0,\ j_t / (d \tan\theta),\ \sqrt{\nu_c \cdot \sigma_B / \Sigma(p_w \cdot \sigma_w) - 1.0}\right\} \quad (5)$$

$$\sum (p_w \cdot \sigma_w) = p_{w2} \cdot \sigma_{wy} + p_{wf} \cdot \sigma_{wf} \quad (6)$$

in which Q_{su} = shear capacity, b = column width, j_t = distance between tensile and compression main bars, ϕ = angle of concrete strut of truss mechanism, d = effective depth, ν_c = effective coeficient of concrete strength, σ_B = concrete compressive strength, H = length of column, p_{w2} = hoop ratio (steel reinforcement), σ_{wy} = yield strength of hoop, p_{wf} = fiber reinforcement ratio, and σ_{wf} = stress of fiber.

In calculating the fiber stress, the following assumptions are made :

(a) The fiber reinforcements contribute to the truss mechanism in the same manner as shear reinforcements of ordinary steel reinforced concrete members. However, only fiber reinforcements placed in the perpendicular direction are effective.

(b) The tensile force of truss mechanism is the summation of forces in the fiber reinforcements and steel reinforcements. It is assumed that steel reinforcements yield at a maximum strength in the case of shear failure. Therefore, the tensile stress of both reinforcements is represented as Eq.(6). In addition, a limit of $\sigma_{wy} \le 25\sigma_B$, which is proposed in the original formula, is ignored.

(c) It is considered that the concrete confinement effect formed by fiber reinforcements changes the angle of concrete compression strut of truss mechanism, and influences the effective concrete compressive strength of the arch mechanism. However, collection of useful data to consider these matters is difficult. In this study, the angle change in concrete compression strut due to fiber reinforcements, and the influence on the effective of concrete compressive strength are ignored.

ANALYTICAL RESULTS AND DISCUSSION

Relationships between calculated fiber stress and structural parameters

Figure 4 shows the relation of calculated fiber stress σ_{wy}, with the concrete compressive strength σ_B, shear span ratio M/QD, axial force ratio η, elastic modulus of fiber E_{fme}, steel reinforcement yield stress ratio $p_{w2}\sigma_{wy}$, and fiber reinforce-ment ratio p_{wf}. The points are distinguished by fiber type (CF or AF) and failure mode of specimen, which is fiber rupture (FR), concrete com-pression without fiber rupture (CC), or not reported (NR).

There are no clear relationships except for fiber reinforcement ratio. In addition, the fiber stress in the case of carbon fibers is larger than for aramid fibers, given the fiber reinforcement ratio.

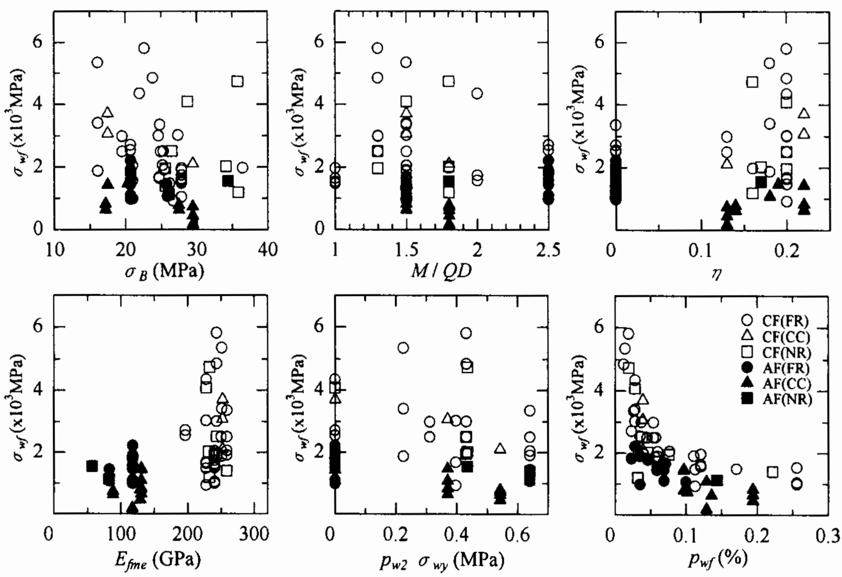

Figure 4. Calculated fiber stress and other factors

Relationships between fiber stress and p_{wf}

From the results given in the former section, calculated fiber stress has an inverse proportional correlation with fiber reinforcement ratio. In addition, the stress in carbon fibers is higher than that in aramid fiber, as fibers with high elastic modulus carry higher stress. Also, fiber strain at the maximum strength of member is inversely proportional to the fiber reinforcement ratio. Furthermore, the product of fiber stress and strain, which has an equal dimension as strain energy, could be correlated with the fiber reinforcement ratio.

The assumptions that the fiber stress σ_{wf}, fiber strain ε_{wf} (= σ_{wf} / E_{fme}) and fiber strain energy U_{wf} (= 0.5 $\sigma_{wf} \cdot \varepsilon_{wf}$) has an inverse proportional relation with the fiber reinforcement ratio p_{wf} are made, and regression analysis by the least square method is carried out. Figure 5 shows these relationships and the results. The data for which failure mode is not reported were excluded in the analysis. The following formulas for σ_{wy}, are obtained, with Eq. (10) as a lower bound value to include 90% of the data considered in Eq.(9).

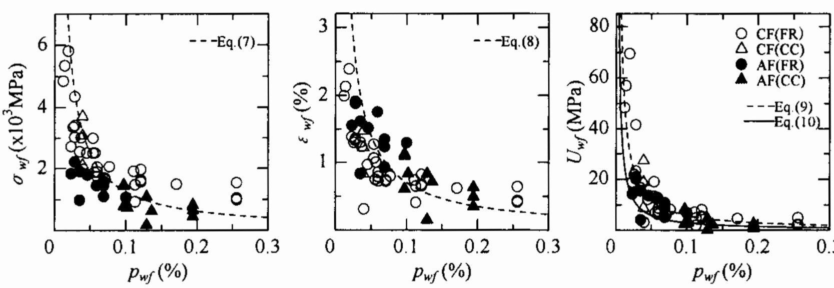

Figure 5. Relationships between σ_{wf}, ε_{wf}, U_{wf} and p_{wf}

$$\sigma_{wf} = 1.25 / p_{wf} \tag{7}$$

$$\sigma_{wf} = 7.0 \times 10^{-6} \cdot E_{fme} / p_{wf} \tag{8}$$

$$\sigma_{wf} = \sqrt{11.8 \times 10^{-3} \cdot E_{fme} / p_{wf}} \tag{9}$$

$$\sigma_{wf} = \sqrt{5.9 \times 10^{-3} \cdot E_{fme} / p_{wf}} \tag{10}$$

Using the fiber stress calculated by Eqs. (7), (8) and (10), the relations of the shear strength calculated by Eq.(1) with observed maximum loads are shown in Figure 6. Eq. (7) tends to overestimate the calculated value for aramid fibers. For Eqs. (8) and (10), there is no significant difference in accuracy of prediction between the types of fibers. These formulas consider the elastic modulus of fibers. The average ratio of experimental to calculated values is 0.92 and 1.16 in the case of Eqs. (8) and (10), respectively. A smaller dispersion is found in using Eqs. (10), as the coefficient of variation is 11%.

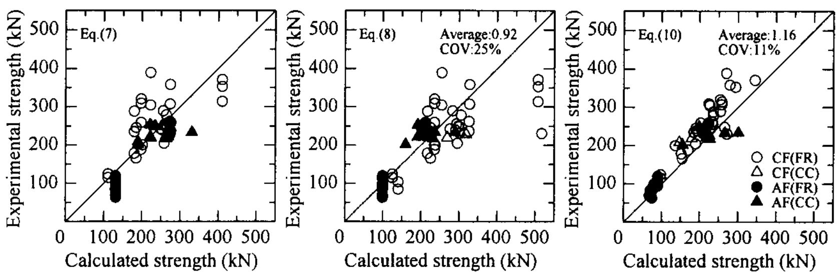

Figure 6. Comparison of calculated strength and experiment

Adaptation for specimens failing after flexural yielding

In this section, the possibility of evaluation using the proposed shear capacity evaluation Eqs. (1) and (10) for specimens which failed after flexural yielding ("failed after yielding" specimens : FAYS) is discussed. A total of 73 specimens of experimental studies on fiber reinforced column specimens are chosen as evaluation targets from References 1, 3, 4, 5, 7, 8, 13 - 27. Of these, 52 specimens were strengthened by carbon fibers and 21 specimens by aramid fibers. Structural parameters of these specimens are listed as follows :

(a) Concrete compressive strength σ_B = 17 – 38MPa
(b) Shear span ratio M/QD = 1.3 – 2.8
(c) Axial force N = 0 – 2500kN
(d) Axial force ratio η = 0 – 0.59
(e) Elastic modulus of continuous fiber E_{fme} = 80 – 520GPa
(f) Hoop ratio (steel reinforcement) p_{w2} = 0 – 0.30%
(g) Fiber reinforcement ratio p_{wf} = 0.01 – 0.44%
(h) Yield strength of hoop σ_{wy} = 300 – 620MPa
(i) Tensile strength of fiber σ_{fme} = 2400 – 4700MPa

Figure 7 shows the relationships between the observed maximum strength Q_{max} and calculated shear strength Q_{su}. Both values are normalized by the calculated bending strength Q_{mu}. This means that FAYS should be plotted on the region where the value of Q_{su}/Q_{mu} is larger than 1. In Figure 7, more than 70% of specimens are plotted in this region, indicating good adaptation of the formulas for FAYS.

Figure 8 shows the Q_{max}/Q_{mu} - Q_{su}/Q_{mu} correlation for all specimens treated in this study. Specimens failed by concrete compression due to bending (C) and those failed by bond of main reinforcements (B) are added. Most of the specimens are evaluated on the safe side. It is recognized that the shear capacity evaluation using Eq. (10) shows good adaptability for fiber reinforced specimens.

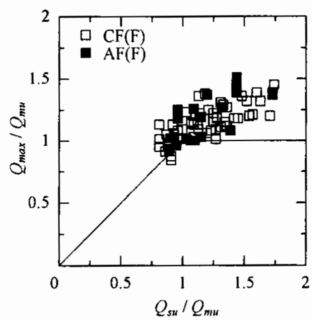

Figure 7. Adaptation for FAYS

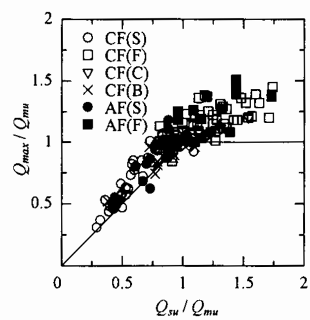

Figure 8. Evaluation for all target specimens

CONCLUSIONS

To propose the evaluation method for shear capacity of RC columns strengthened with continuous fiber, stresses of fibers are calculated backwards using the arch-truss method. The followings are concluded from the results.

(a) The fiber stress, strain and strain energy have an inverse proportional correlation with fiber reinforcement ratio. Prediction formulas for these values are proposed.
(b) Shear capacity of fiber reinforced specimens can be evaluated with a smaller dispersion in case of strain energy.
(c) The proposed formula also shows a good adaptability for specimens failing after flexural yielding.

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