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ESTIMATION OF SHEAR CAPACITY OF REINFORCED CONCRETE COLUMN WITH STEEL FIBERS

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SUMMARY

This paper presents a empirical equation for evaluating the effects of steel fiber reinforcement on the shear capacitiy of reinforced concrete columns. The equation is based on the experimental information that the increment by fibers was roughly independent of that one by conventional hoop in the columns with both the reinforcements, and based on the assumption that the tensile capacity of steel fiber reinforced concrete at the yielding of hoops across shear cracks could be effective on the shear capacity. It was shown that the proposal equation could estimate almost the available test values within the relative error of 15%.

INTRODUCTION

It has been demonstrated that steel fiber reinforcement in concrete structural members is effective in controlling the propagation and widening of cracks, enhancing the shear capacity and ductility, and preventing the concrete cover from spalling after reaching the ultimate loading capacity (Refs. 1-4). Steel fibers can be utilized either to replace or cooperate with conventional reinforcing steel bars. Considering steel fibers as shear reinforcement, the reinforced concrete members with shear reinforcement of steel fibers alone might produce brittle failures prematurely after flexural yielding (Ref. 5). In the current design where the ductility of members after flexural yielding is required, therefore, it is essential to establish the method of evaluating the effects of steel fibers on the shear capacity in reinforced concrete members with both of steel fibers and conventional stirrups or hoops as shear reinforcement. However, the quantitative effectiveness of steel fibers in such members has not been sufficiently clarified, although there have been some references (Ref. 6), particularly in the members with rather small shear span to effective depth ratio, such as columns.

This research has carried out with the intention of determining the effects of steel fibers on the shear capacity of reinforced concrete columns with a small amount of conventional hoops. First, the composite effects of steel fibers and conventional hoops are investigated in the test series on column-like models without axial force in which the principal variables were the volume fraction of steel fibers and the hoop ratio, and then the equation for evaluating the shear capacity is derived by the regression analysis on the test values. Thereafter, the influence of the axial force is added to the regression equation above. In regard to the treatment of shear span to effective depth ratio, the validity is examined in the application of the equation. Finally, the accuracy of the equation is discussed including the data from other researchers.

CONSTRUCTION OF ULTIMATE SHEAR CAPACITY EQUARION

Table 1 shows the test series on reinforced concrete columns with use of steel fibers and conventional hoops in combination, and the main valiables in each series, where in all the columns shear failures prior to flexural yielding have been reported. In all the series horizontal loading was performed under a fixed vertical load, including no vertical load, while the rotations were restrained at the top and bottom, as illustrated in Fig. 1. In the series ANO, AN1 and AN2 horizontal loads were increased monotonically, but in the other sesies they were applied cyclic reversally several times up to the ultimate capacity. Except for the series RF (Ref. 7) in Table 1, all the other series were carried out by the author and cooperators (Refs. 8-16), although the designations of series were used only here for convenience's sake. Fig. 2 shows the outline of typical column specimen used in the series N2, N3 and ANO.

Table 1 Main Variable in Past Available Test Series on R/C Columns with Steel Fibers

Designation of Test Series	Number of Specimens	Fiber Shape and Length	σ_c kgf/cm²	b×D cm	h_0/D	p_w %	V_f %	p_t %	σ_0 kgf/cm²
RF[2)]	7	Waved, 25mm	286 ~343	25×25	2.0	0.48, 1.72	1.0, 2.0	1.27, 0.96	32 ~96
N1[3)]	8	Waved, 25mm	332 ~404	20×20	3.0	0.2	0, 1.0 ~2.0	0.95	75
N2[4)]	22	Waved, 25mm	353 ~404	20×20	3.0	0 ~0.46	0, 1.0 ~2.0	2.14	0 ~75
N3[5)]	12	Waved, 25mm	308 ~464	20×20	3.0	0 ~0.46	0, 1.0 ~2.0	2.14	0 ~75
AF[6)]	13	Flat 30mm	298 ~420	20×20	3.0	0.2	0, 1.0 ~1.75	0.95	75
AFL[7)]	3	Flat 30mm	292 ~308	40×40	3.0	0.2	0, 1.0 ~1.5	0.95	60
ANO[9),10)]	34	Flat, waved, 30mm	244 ~360	20×20	2.0 ~4.0	0 ~0.46	0, 1.0 ~2.0	2.14	0
AN1[11)]	8	Flat, 30mm	254 ~350	20×20	3.0	0.2	1.0	2.14	0 ~75
AN2[11)]	11	Flat, 30mm	272 ~375	20×20	2.0 ~4.0	0.2	0, 1.0	2.14	-25 ~180
AFT[8)]	10	Indent, Waved Hook, 30mm	203 ~266	20×20	3.0	0.2	0, 1.0	0.95	75

b =Column Width, D =Column Depth, h_0 =Column Clear Length
p_t =Tension Steel Reinforcement Ratio , p_w =Hoop Ratio
V_f =Volume Fraction of Fiber, σ_c = Compressive Strength of SFRC
σ_0 =Axial Stress by Fixed Vertical Load (Positive in Compression)

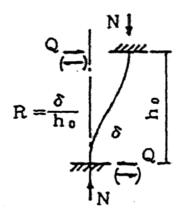
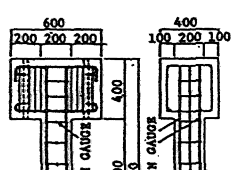


Fig. 1 Loading Condition



6-D19(p_t=2.14%), Hoop D6 @140mm(p_w=0.23%)

Fig. 2 Outline of Typical Specimen

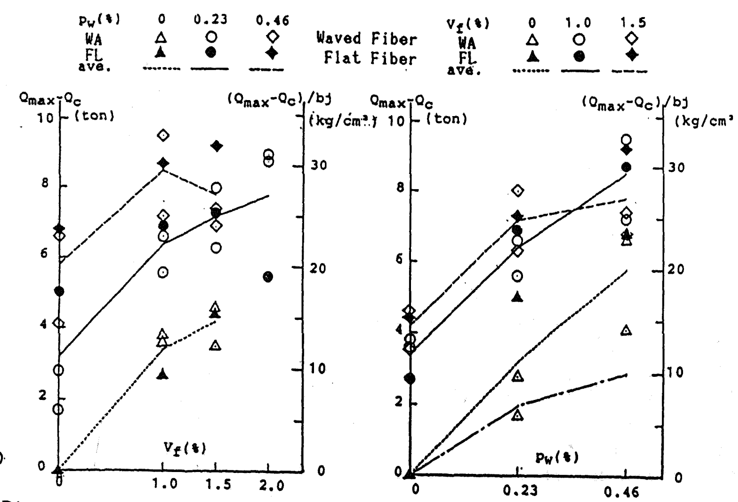


Fig. 3 Influence of Fiber Volume Fraction, V_f and Hoop Ratio, p_w

Informations from Test Results Fig. 3 shows the influences of fiber volume fraction, V_f and conventional hoop ratio, p_w in the columns with $h_o/D=3$ and without axial force, obtained from the series ANO, where the ordinate, $(Q_{max}-Q_c)$ or $(Q_{max}-Q_c)/bj$ indicates the capacity assumed to be carried by the steel fibers and hoops; Q_{max} and Q_c denote the ultimate capacity and the capacity carried by the concrete including the resistance by aggregate interlock and dowel actions, respectively; and b and j denote the column width and the seven eighths of effective depth, respectively. Here, Q_c is calculated from the following equation:

$$Q_c = Q_{c0} \times (\sigma_c / \sigma_{c0})$$

where

Q_{c0}=shear capacity of the column without hoops and fibers;
σ_{c0}=compressive strength of concrete used in the above column; and
σ_c=compressive strength of concrete or fibrous concrete used in a column.

And also the chain line on the right of the figure indicates the relation obtained from $2.7\sqrt{p_w \sigma_{wy}}$, the term related to shear reinforcing steel bars in Arakawa's ultimate shear capacity equation (Ref. 17), for reference. Now, from Fig. 3, the following observations are obtained:

(1) The shear capacity increases with increasing the fiber content and hoop one.
(2) The rate of increasing shear capacity is reduced with each content.
(3) The increment by fiber reinforcement and the one by hoop reinforcement are almost independent each other.

Shear Resistance Mechanism Based on the observations (1) and (3) described in the preceding paragraph, the ultimate shear capacity of reinforced concrete column with steel fibers and conventional hoops as shear reinforcement was assumed to be expressed as follows:

$$Q_{su} = Q_c + Q_w + Q_{SF}$$

where

Q_{su}=ultimate shear capacity;
Q_c =shear force carried by concrete, including resistances by aggregate interlock and dowel actions;
Q_w =shear force carried by hoops; and
Q_{SF}=shear force carried by steel fibers across shear crack.

Further,

$$Q_{SF} = b\ j\ \sigma_{tu} \cot\theta$$

where

σ_{tu}=tensile capacity of fibrous concrete, called SFRC, at yielding of hoops

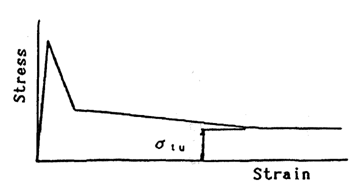
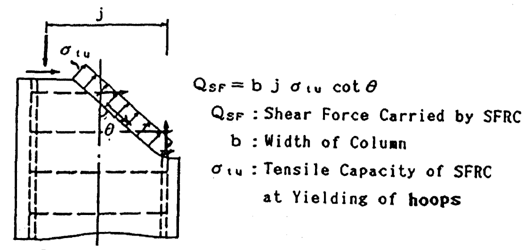


Fig. 4 Idealized Stress−Strain Relation of SFRC in Tension Range



$Q_{su} = Q_c + Q_w + Q_{SF}$
Q_c =Shear force carried by concrete, including resistance by aggregate interlock and dowel actions
Q_w =Shear force carried by web reinforcement (hoops)
Q_{SF}=Shear force carried by steel fibers across shear crack

Fig.5 Shear Resistant Elements at Shear Crack in Reinforced Concrete Columns with Steel Fibers

Figs. 4 and 5 illustrate these resistant elements at shear crack and the residual tensile capacity of fibrous concrete, σ_{tu}, respectively. It should be emphasized herein that the residual tensile capacity represents the one developed in excess of the yield strain of hoop bars, because at the ultimate shear capacity the yielding of hoops was observed in most of the test specimens mentioned above.

Regression Analysis From the observations of test results and the assumptions mentioned above, the ultimate shear capacity equation for reinforced concrete columns with steel fibers and hoops in combination was assumed to be expressed in the form of the following equation, following Arakawa's equation modified by Hirosawa (Ref. 17):

$$\frac{Q_{su}}{b \cdot j} = \tau_{su} = c_1 \frac{k_u \cdot k_p \ (\sigma_c + 180)}{(a/d + 0.12)} + c_2 \sqrt{p_w \cdot \sigma_{wy}} + c_3 \sqrt{V_f} + c_4 \cdot \sigma_0$$

where c_1 to c_4 are regression coeffecients to be determined later; k_u and k_p are correction factors due to effective depteh of column, d and tension steel reinforcement ratio, pt, respectively; a is shear span; and the other notations refer to the footnote of Table 1.

First, the coefficients c_1 to c_3 were determined to be 0.0816, 4.55, 9.51 by analyzing the results of test specimens, the total number of 53, drawn under the condition of σ_0=0 and ho/D=3 from the series ANO, N2 and N3 in Table 1, where those specimens were considered almost identical in sectional and material properties except for fibers slightly different in shape and length. In the above analysis the average value and variation coefficient was 1.00 and 9.68%, respectively, on the ratio of tested value to calculated one. Fig. 6 shows the comparison of tested values with calculated ones. From the figure most of the tested values are observed to be estimated within the error of 15% of the corresponding calculated values. Further, the analysis by each original series was carried out, although there was not found a significant difference from the above results.

Then, the coefficient c_4 was determined to be 0.110 by analyzing the results of specimens, the total number of 13, drawn under the condition of ho/D=3 and V =1% from the series AN1 and AN2 in Table 1 in which all the specimens had pw of 0.2%, although the specimens subjected to tensile axial force were excluded. In this analysis the average value and variation coefficient were 1.00 and 5.84%, respectively, on the same ratio as mentioned above.

After all the ultimate shear capacity equation was determined as follows:

$$\frac{Q_{su}}{b \cdot j} = \tau_{su} = 0.0816 \frac{k_u \cdot k_p \cdot (\sigma_c + 180)}{(a/d + 0.12)} + 4.55\sqrt{p_w \cdot \sigma_{wy}} + 9.5\sqrt{V_f} + 0.1\sigma_0$$

In the application of the above equation, the tensile strength of fibers should be so high that the tensile capacity of fibrous concrete will deteriorate not by the rupture of fibers but by the bond failure of fibers, as shown in the idealized stress-strain relation in Fig. 5. And also, the fibers should be straight-like and have a little or not deformed surface.

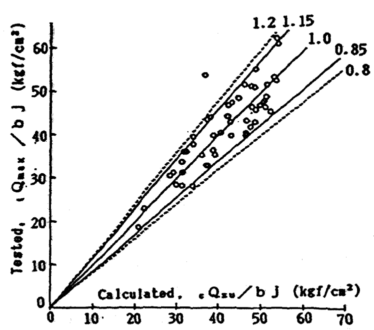


Fig. 6 Comparison of Tested with Calculated

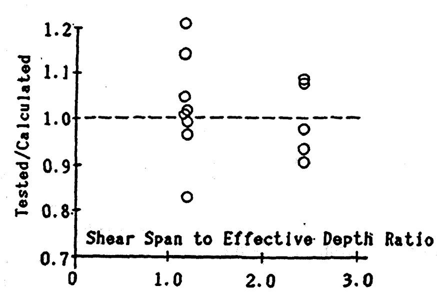


Fig. 7 Tested/Calculated Ratio versus Shear Span to Effective Depth Ratio

DISCUSSIONS

Examination on Shear Span to Effective Depth Ratio The ultimate shear capacity equation was derived under the condition of $h_o/D=3$. Fig. 7 shows the comparison of the ratio of tested/calculated with the shear span to effective depth ratio, on the specimens drawn under the condition of $h_o/D \neq 3$ and $V_f=1\%$ from the series RF, AN0 and AN2 in Table 1. From the figure, somewhat larger scattering is observed near 1 of the shear span to effective depth ratio. However, it is also observed that most of the tested values can be estimated within the error of 15% of the corresponding calculated values. Therefore, it is supposed that the effects of shear span to effective depth ratio on the capacity could be estimated in the form of Arakawa's equation.

Examination of Accuracy Fig. 8 shows the frequency distribution of the ratio of tested/calculated computed on all the specimens in Table 1, the total number of 128, using the proposal equation. Table 2 shows the accuracy on the ratios of tested/calculated by the equation, examined from some interesting view points. From the table, it is found that about 95% of all the data can be estimated within the relative error of 15%, although the independent data of the foregoing regression analysis resulted in somewhat lower accuracy. The lower limit of the ratio of tested/calculated was 0.85 which satisfies the still percentage of passing of 95%. The accuracy resulted a little lower in the presence of axial force than in the absence. Concludingly, it can be pointed out that the accuracy of proposal equation might be higher than or equal to that of the ultimate shear capacity equation for conventional reinforced concrete members, even in the case of conventional reinforced concrete columns without steel fibers.

CONCLUSIONS

From the test results on reinforced concrete columns with use of steel fibers in conjunction with conventional hoops, the following conclusions were obtained:
(1) The shear capacity increased with the content of steel fibers, but the increment was reduced with increasing the fiber content.
(2) The effects of fibers and conventional hoops on the shear capacity were almost independent each other.
(3) The influences of shear span to effective depth ratio and axial force on the shear capacity were almost the same as those in conventional reinforced concrete columns without steel fibers.
(4) The empirical equation proposed for predicting the ultimate shear capacity can estimate almost the test values, available so far, within the relative error of 15%.

It should be also mentioned in addition that the above conclusions would be complemented by further studies, because they were obtained under limited conditions.

Table 2 Accuracy of Proposal Equation

viewpoint	number of data	Av	Vc (%)	passing rate,% P-15	P-20
all of data	128	1.01	11.2	82.0	95.3
dependent data	66	1.00	9.3	90.9	100
independent data	62	1.02	12.8	72.6	90.3
axial presence	67	1.01	11.2	76.1	92.5
force absence	61	1.01	11.2	88.5	98.4
steel presence	108	1.01	10.9	84.3	95.4
fiber absence	20	1.01	12.8	70.0	95.0

note: 1) Av and Vc are the average value and variation coefficient of tested/calculated ratio, respectively.
2) The above "dependent" or "independent" means dependent or independent of the regression analysis.
3) P-15 and P-20 mean still passing rate satisfying 15 and 20% the upper limit of relative error, respectively.

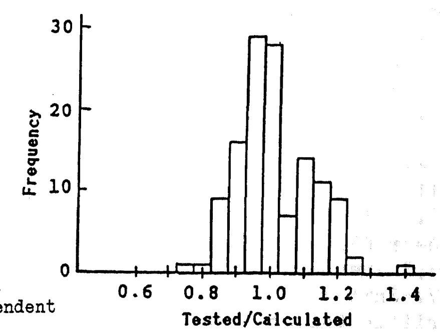


Fig. 8 Frequency Distribution of Tested/Calculated Ratio

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