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# Behavior of Steel Fiber Reinforced Concrete Columns under Cyclic Loading

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**Abstract**

To improve the brittle column behavior during seismic excitation, benefits of using steel fiber reinforced concrete in columns were investigated. For experimental study, eight specimens were used to evaluate the shear enhancement effect. The variables in this study were amount of shear reinforcement ratio (i.e., 0.26, 0.21 %) and steel fiber volume fraction (i.e., 0.0, 1.0, 1.5, 2.0 %). The test results indicated that the maximum enhancement of shear capacity was shown in 1.5 % steel fiber content. In addition, to predict the maximum shear strength, equations of ACI 318-99, AIJ MB, NZS 3101, Hirosawa and Priestley were reviewed. From the parametric and regression study, modified Priestely equation was proposed by adding steel fiber effect.

***Keywords: steel fiber, volume fraction, aspect ratio, shear, strengthening effect, column***

## 1. Introduction

Low story columns of high-rise buildings can be subjected to high shear stresses caused by seismic force, and are apt to brittle shear failure which can lead to make a collapse of the whole building structure. Therefore, design codes specify shear reinforcing methods and rebar placing details to prevent brittle failure. However, heavily laid shear reinforcement in columns can cause difficulties in concrete pouring. Addition of steel fiber in concrete significantly improves many of the engineering properties of concrete, notably shear strength. Flexural strength, fatigue strength, and the ability to resist cracking also enhance. Especially, the benefits of steel fibers in shear could be in preventing brittle shear failure. A number of laboratory tests were conducted to determine the effect of adding steel fibers in many countries which focus on flexural and shear capacity of beams. However, the researches in reinforced concrete columns strengthened by steel fiber were focused not on deformation capacity but on strength capacity.

The purpose of this study was to define the shear strengthening effect of steel fiber reinforced concrete (SRFC) columns through a review of literatures and experiments. To achieve the goal of this study, followings were performed.

Review previous studies: Define the adequate steel fiber volume fraction in concrete.

(1) Perform structural test of SFRC columns: Prove and redefine the adequate steel fiber content by studying strength, ductility, stiffness degradation, and energy dissipation.
(2) Review existing shear strength prediction equations.

The research results from previous studies are as follows: Masuta (1997), Nagasaka (1990), Yashiro (1989), Makitani (1985), and Sakai (1979). The parameters of those studies were shear-span-to-depth ratio (a/d or M/Vd), shear reinforcement ratio, steel fiber content, and axial force. The results were evaluated by shear capacity ratio, which is a maximum shear load divided by square root of compressive strength of concrete and effective cross section. Based on these studies, tests were planned varying steel fiber contents ($V_f$) and shear reinforcement ratios. Detailed test variables were as follows:

(1) Design compressive strength of concrete: 24 N/mm$^2$

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(2) Shear reinforcement ratio (%, Av/bs, s: spacing of shear reinforcement): 0.26, 0.21
(3) Steel fiber volume fraction (%, by volume): 0.0, 1.0, 1.5, 2.0
(4) Steel fiber shape and aspect ratio: hooked end, 63.6 (length/diameter=33/0.55)
(5) Testing method: lateral load revesered cyclic test with constant axial load (10% of axial capacity)
(6) Number of testing specimens: 8 each

Also to compare the shear strength of steel fiber reinforced columns using the test results, design code of U.S.A (ACI 318-99, 1999), Japan (AIJ MB, 1997), New Zealand (NZS 3101, 1989), and proposed equations of Hirosawa (1990) and Priestley (1994) were examined.

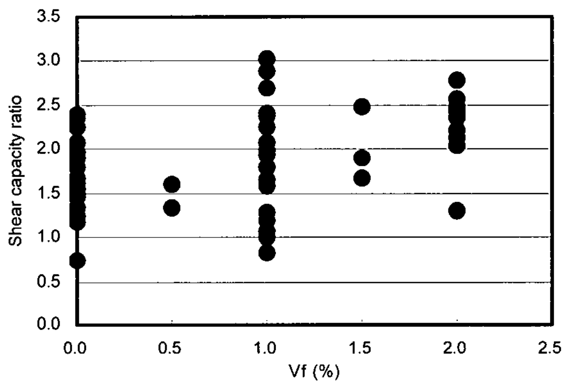
## 2. Review of previous studies

From the study of Masuta (1997)[1)], Nagasaka (1990)[2)], Yashiro (1989)[3)], Makitani (1985)[4)], Sakai (1979)[5)], the useful data for SFRC columns were obtained. They considered steel fiber content, shear-span-to-depth ratio (a/d), and shear reinforcement ratio.

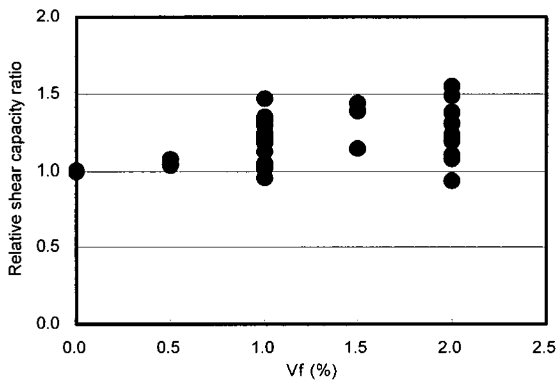
To analyze the benefits of using steel fiber on the shear strength, shear capacity ratio (SCR, Eq. (1)) was used. Test results of 50 specimens were evaluated as shown in Fig. 1.

$$SCR = \frac{V_u}{\sqrt{f_{ck}}\,bd} \quad (1)$$

In Fig. 1 (a), the correlation between $V_f$ and SCR was unclear. Therefore, the relative SCR (RSCR), SCR of steel fiber reinforced specimens divided by SCR of non-reinforced specimen with the same size and the same reinforcement conditions, was considered in order to find the correlation. From the RSCR according to $V_f$ in Fig. 1 (b), linear correlation between RSCR and $V_f$ is evaluated. Adding the statistic investigation to the RSCR in Fig. 1 (b), the mean value and standard deviation of RSCR are calculated as 1.06, 1.20, 1.32, 1.25 and 0.03, 0.15, 0.16, 0.20 corresponding to $V_f$ of 0.5%, 1.0%, 1.5%, and 2.0%, respectively. From this, the optimum steel fiber content for the maximum shear capacity enhancement is 1.5%. In case of 2.0% $V_f$, the shear strengthening effect of steel fiber is deteriorated due to steel fiber-balling during concrete mixing and placing state.




(a) Shear capacity ratio vs. steel fiber volume fraction ($V_f$)




(b) Relative shear capacity ratio vs. $V_f$

**Fig. 1** Results of previous studies

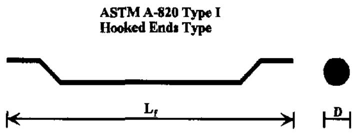
## 3. Testing program

Shear capacity enhancement effect of steel fiber in normal strength concrete can be evaluated by testing the steel fiber-strengthened versus no-strengthened specimens. For the purpose of comparison, two specimens without steel fiber and six specimens with steel fiber were tested. The specimens were divided into two series by the shear reinforcement ratio ($\rho_w$). The shear reinforcement ratios of S1 series and S2 series were 0.26 % and 0.21%, respectively.

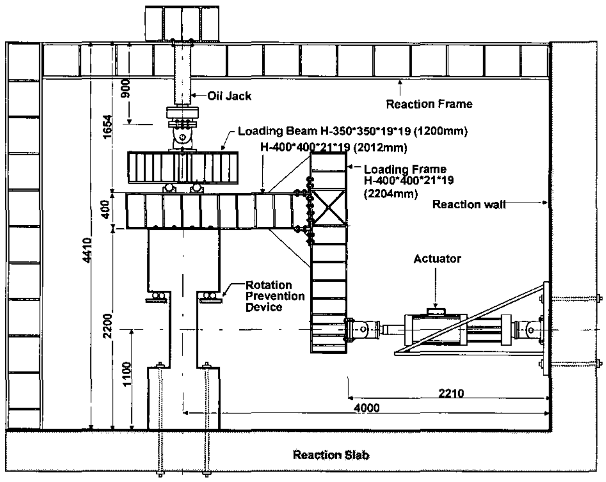
List of test specimens is shown in Table 1 contani specimen name, steel fiber content, and tested compressive strength of concrete. Used steel fiber is hooked end type of ASTM A-820 type 1 and is shown in Fig. 2 (a). Steel fiber percentages of 1.0, 1.5 and 2.0 % in each volume fraction of concrete are used. Specimen setting with loading devices is presented in Fig. 2 (b).

**Table 1** List of specimens

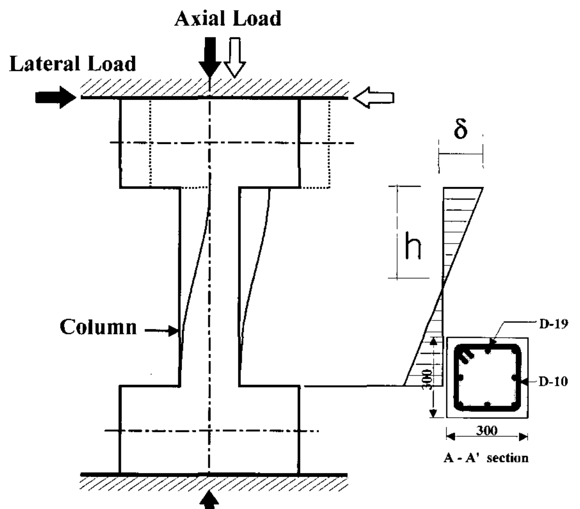
| Specimen name | | $V_f$ (%) | $f_{ck}$ (N/mm$^2$) |
|---|---|---|---|
| S1 series ($\rho_w$= 0.26%) | S1-0.0-N | 0.0 | 27 |
| | S1-1.0-N | 1.0 | 27 |
| | S1-1.5-N | 1.5 | 28 |
| | S1-2.0-N | 2.0 | 25 |
| S2 series ($\rho_w$= 0.21%) | S2-0.0-N | 0.0 | 27 |
| | S2-1.0-N | 1.0 | 27 |
| | S2-1.5-N | 1.5 | 28 |
| | S2-2.0-N | 2.0 | 25 |



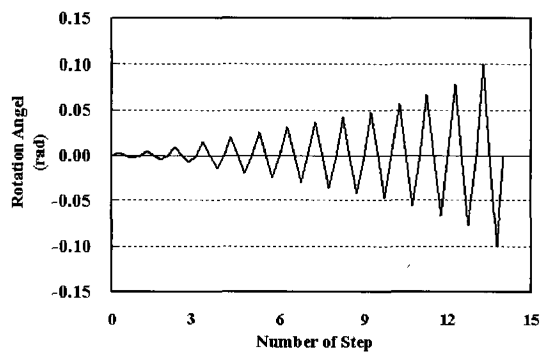

(a) Shape of steel fiber




(b) Specimen setting plan




(c) Double curvature modeling




(d) Loading history

**Fig. 2** Testing apparatus and method

**Table 2** Test results

| Specimen | Main bar yielding | | Stirrup yielding | | Maximum Load | |
|---|---|---|---|---|---|---|
| | $V_{my}$(kN) | $\delta_{my}$(mm) | $V_{sy}$(kN) | $\delta_{sy}$(mm) | $V_{max}$(kN) | $\delta_{max}$(mm) |
| S1-0.0-N | - | - | 215 | 32.94 | 216 | 18.00 |
| S1-1.0-N | 167 | 23.32 | 82 | 28.14 | 228 | 17.16 |
| S1-1.5-N | 200 | 26.88 | - | - | 270 | 22.30 |
| S1-2.0-N | 209 | 43.22 | - | - | 322 | 22.54 |
| S2-0.0-N | - | - | 115 | 19.44 | 200 | 17.95 |
| S2-1.0-N | - | - | 143 | 29.71 | 218 | 20.98 |
| S2-1.5-N | 193 | 26.44 | - | - | 239 | 18.08 |
| S2-2.0-N | 218 | 27.06 | - | - | 262 | 13.34 |

- Did not yield

Applied axial force was a constant load equivalent to 10% of nominal strength of the column section. Column shear test was performed so as to enforce the double curvature deformation as shown in Fig. 2 (c). Applied lateral force created by rotational angle ($\tan\theta \cong \delta / h$) is shown in Fig. 2 (d). For all the column specimens, the cross section was 25 × 25 cm, the height was 90 cm, and the ratio of shear span-to-depth was 1.5. Tension reinforcement ratio ($\rho = A_s/bd$) was 1.2 %, and shear reinforcement ratios ($\rho_w = A_v/bs$) used in this test were 0.26 %, 0.21 %, respectively. During the test, rebar strain and member displacement were measured by strain gauges and LVDTs.

## 4. Test results

The cyclic lateral load test results such as yield and maximum load as well as displacement are shown in Table 2. In Table 2, shear reinforcement yielded before tension reinforcement in the specimens which were made without and with low steel fiber contents. On the contrary, when steel fiber content is increased to 1.5 and 2.0%, the tension reinforcement yield before the shear reinforcement. From the failure mechanism, the steel fiber effect in resisting shear mechanism in SFRC is clearly shown. And if steel fiber content is properly selected in SFRC columns such as $V_f$ 1.5 % or 2.0 %, failure mode could be changed from brittle shear failure to ductile flexural by the addition of steel fiber. From the load-displacement curves for the S1 series, which are shown in Fig. 3, maximum shear strength increase as steel fiber contents is increased. In addition, steel fiber effect in improving ductility, stiffness, and energy capacity is clear in Fig. 3. Failure crack patterns for the S2 series are shown in Fig. 4. In general, crack patterns are complex and it is difficult to find the appropriate steel fiber effect in the cracking patterns. Nevertheless, it is shown that crack patterns change from brittle shear crack to flexural as the fiber contents is increased in Fig. 4.

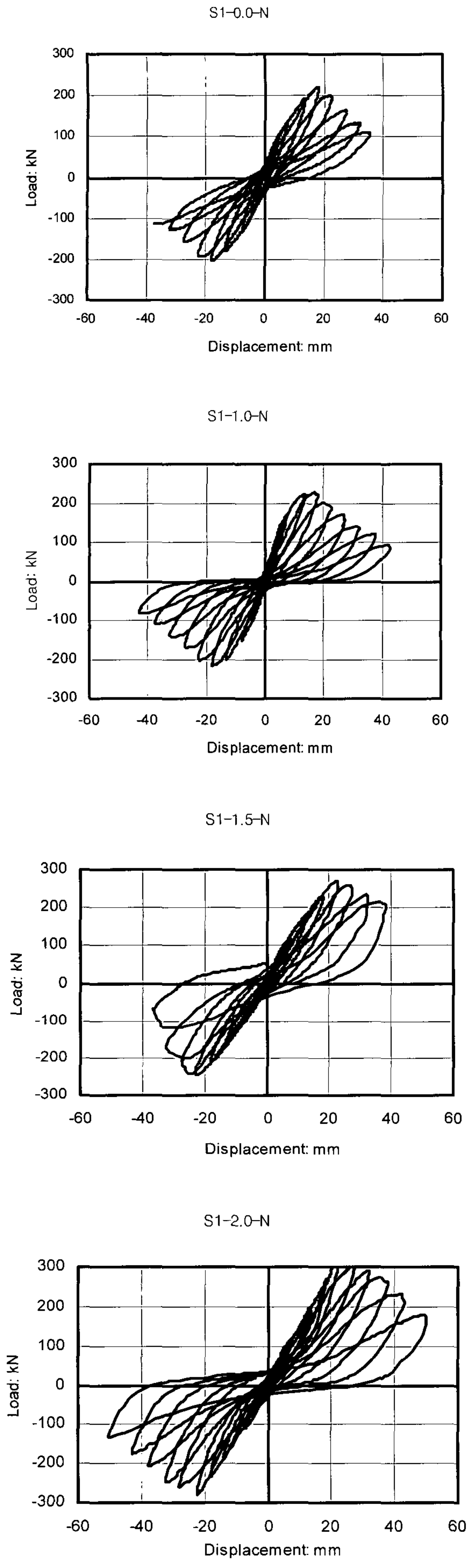



**Fig. 3** Load-displacement curves for S1 series

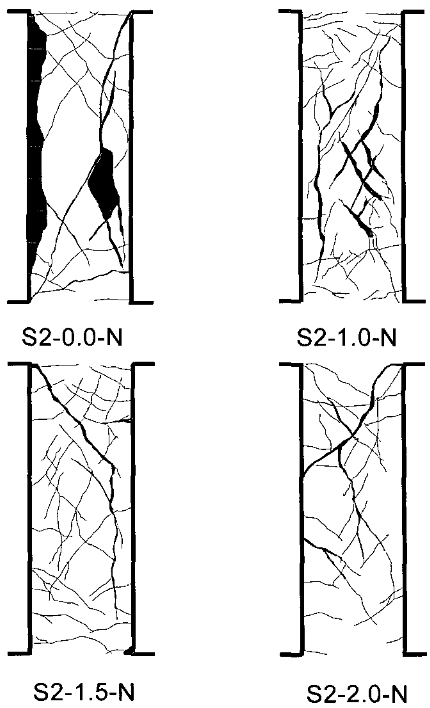



**Fig. 4** Failure shape for S2 series

## 5. Discussion of steel fiber effects

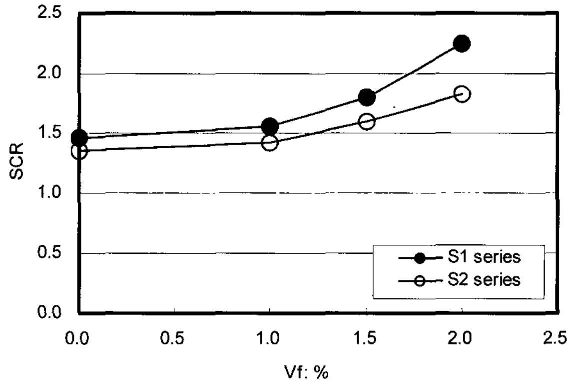
The shear capacity ratio (SCR) of Eq. (1) was used for the evaluation of steel fiber effects. In Table 3 SCR and ductility ratio are listed. In Fig. 5 (a), SCR is plotted by steel fiber content for each shear reinforcement ratio. From the figures, use of 1.0% steel fiber in concrete does not make good enhancement in SCR but use of steel fiber such as 1.5% and 2.0% greatly enhance the performance in SCR. It is noted tha the effet of the steel fiber content on the SCR current test results were showed somewhat different from previous researches.[1-5] In case of 1.0 % steel fiber, SCR values of the current results are lower than those from previous researches.

However in case of 1.5% and 2.0 % steel fiber additions, SCR values are similar to and higher than those from previous researches, respectively. These differences came from the workability of SFRC. The fiber-balling phenomenon might have caused improper distribution of steel fibers in the case of 2.0 % volume fraction in previous studies. On the contrary, fiber-balling in this test was very little. Therefore, the SCR increased in proportion to $V_f$.

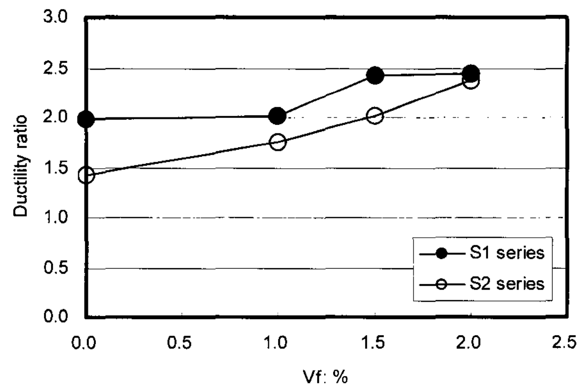
As shown in the load-displacement curve of Fig. 3, it is difficult to find the yield point. Therefore, yield point ($\mu_y$) is evaluated at a 75 % of maximum strength. To calculate the ductility ratio ($\mu = \mu_{max} / \mu_y$), ultimate displacement ($\mu_{max}$ ) is evaluated at an 80 % of maximum test strength after the maximum state.[6] In Table 3 and Fig 5 (b), ductility ratio increases as steel fiber content increases. In S1 series,

**Table 3** Shear capacity and ductility ratio

| Specimen name | Shear capacity ratio (SCR) | Ductility ratio (μ) |
|---|---|---|
| S1-0.0-N | 1.46 | 1.98 |
| S1-1.0-N | 1.55 | 2.02 |
| S1-1.5-N | 1.80 | 2.43 |
| S1-2.0-N | 2.25 | 2.45 |
| S2-0.0-N | 1.36 | 1.43 |
| S2-1.0-N | 1.42 | 1.76 |
| S2-1.5-N | 1.59 | 2.02 |
| S2-2.0-N | 1.83 | 2.38 |




(a) Evaluation of strength capacity

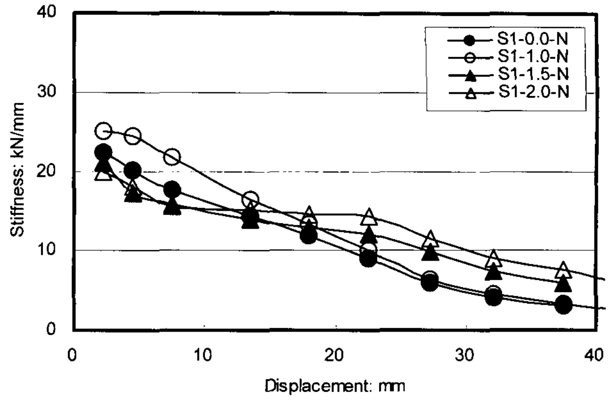



(b) Evaluation of deformation capacity

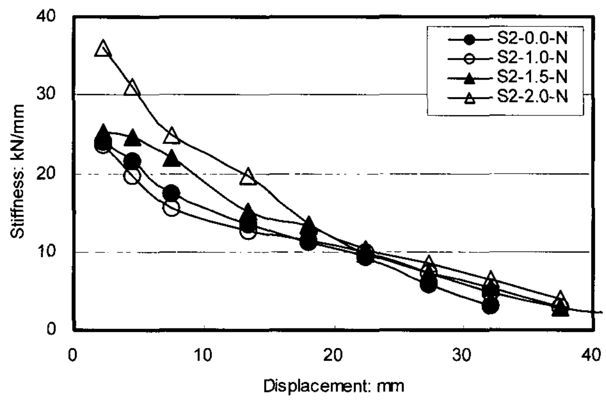
**Fig. 5** Comparison of strength and deformation capacity

ductility capacities, where $V_f$ = 1.5% and $V_f$ = 2.0% are almost the same. This is also found in the load-displacement curves of S1-1.5-N and S1-2.0-N in Fig. 3. This result is due to the steel fiber-balling in concrete. From the results, it can be implied the adequate steel fiber contents to improve shear capacity and ductility capacity is suggested as 1.5 % volume fraction of concrete.

Stiffness degradation and energy dissipation of S1 series and S2 series are shown in Fig. 6 and Fig. 7. From the fig.




(a) Stiffness degradation (S1 series)




(b) Stiffness degradation (S2 series)

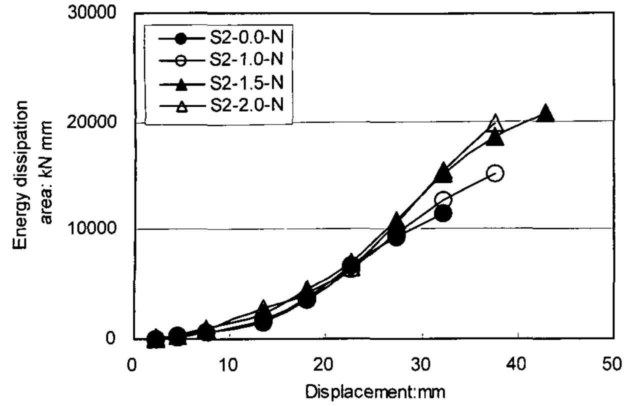
**Fig. 6** Comparison of stiffness degradation

the steel fiber effect is not produce in pre-yield state. But after the yield state, the effect of steel fiber is revealed to reduce the stiffness degradation ratio and increase the energy dissipation capacity. Therefore beneficial effects of steel fiber in terms of stiffness and energy dissipation capacity are shown in post-yield state.

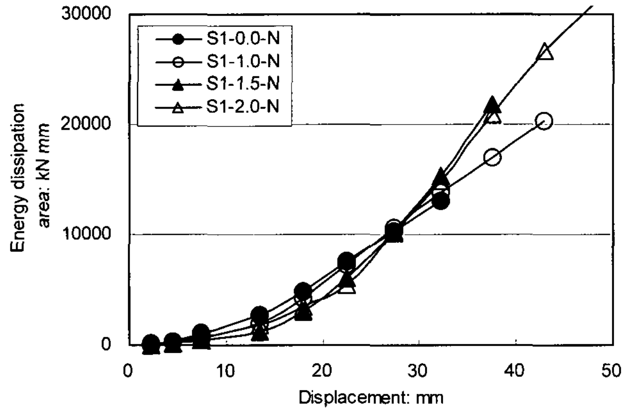
## 6. Prediction of shear strength

### 6.1 Proposed equations

To predict the maximum shear strength of steel fiber reinforced columns, five equations which considered axial load effect were used as follows: Eq. (2)[7], Eq. (3)[8], Eq. (4)[9], Eq. (5)[10], and Eq. (6).[11] Even though these equations do not have steel fiber parameter, the compressive strength of concrete can represent steel fiber effect in shear resisting mechanism[12]. And this was also found in Table 2, where the compressive strength of concrete increased up to $V_f$ 1.5 %.




(a) Energy dissipation area (S1 series)




(b) Energy dissipation area (S2 series)

**Fig. 7** Comparison of Energy dissipation area

$$V_n = V_c + V_s,\ V_c = 2(1 + N_u/2000A_g)\sqrt{f_c'}b_w d \quad (2)$$

$$V_s = (A_v f_y d)/s \quad \text{- in psi}$$

$$V_u = bj_t p_w \sigma_{wy} + (\gamma - \alpha\beta)bD\sigma_B \quad (3)$$

In case of $n \le 0.5 - 2\phi$

$$\gamma = \frac{1}{2}\{\sqrt{4(n+2\phi)(1-n-2\phi) + (\frac{2M}{VD})^2} - \frac{2M}{VD}\}$$

In case of $n > 0.5 - 2\phi$

$$\gamma = \frac{1}{2}\{\sqrt{1 + (\frac{2M}{VD})^2} - \frac{2M}{VD}\} \quad \text{- in Pa}$$

$$V_n = V_c + V_s \quad (4)$$

$$V_c = v_b(1 + 3P/f_c'A_g)b_w d,\ V_s = (A_v f_y d)/s,$$

$$v_b = (0.07 + 10\rho_w)\sqrt{f_c'} \quad \text{- in Pa}$$

$$Q_{su} = \{\frac{0.0679 p_t^{0.23}(180 + \sigma_B)}{M/(Qd) + 0.12} + 2.7\sqrt{P_w \sigma_{wy}} + 0.1\sigma_0\}bj \quad (5)$$

- in Pa

$$V_n = V_c + V_s + V_p,\ V_c = k\sqrt{f_c'}A_e \quad (6)$$

$$V_p = P\tan\alpha,\ V_s = (A_v f_{yh} D\cot 30)/s \quad \text{- in psi}$$

### 6.2 Parametric study for proposed equations

To evaluate the adaptability of proposed equations, steel fiber non-reinforced case is considered. Test results (i.e., $V_{test}$) of 25 specimens from previous[1-5] and the curent studies were calculated as $V_{calculation}$. Statistical results of relative ratio ($V_{test}$ / $V_{calculation}$) are listed in Table 4. Among the listed value of mean and standard deviation, the results of AIJ MB and Priestley are shown to be very conservative than others. The mean of AIJ MB and Priestley are 0.89 and 0.83, respectively, and standard deviation of AIJ MB and Priestley are 0.22 and 0.26, respectively. According to the ultimate strength design method, shear strength reduction factor ($\phi$) is 0.85, where 0.85 means lower bound to tested data. Therefore, calculated results by Priestley are more conservative and safer than the results by AIJ MB. To considered steel fiber effects in column shear, relative ratio ($V_{test}$ / $V_{calculation}$) of 60 specimen results, which included non-reinforced and reinforced steel fiber are plotted by steel fiber content in Fig. 8. From the figure, correlation between steel fiber content and the ratio of $V_{test}$ over $V_{calculation}$ is proved to be linear from the regression analysis. Consequently, beneficial effect of steel fiber in shear strength could be derived using of steel fiber content.

### 6.3 Estimation of steel fiber effects

To estimate the steel fiber effect, relative shear capacity ratio (RSCR), which is SCR ratio of steel fiber reinforced over non-reinforced in same material and dimensional conditions, is introduced. Results of RSCR for 50 specimens were represented in Table 5 and in Fig. 9. From the results, it was found that RSCR increased linearly as steel fiber

**Table 4** Statistical estimation of steel fiber non-reinforced Columns

| | $V_{test}$ / $V_{calculation}$ | | | | |
|---|---|---|---|---|---|
| | ACI 318-99 | AIJ MB | NZS 3101 | Hirosawa | Priestley |
| Mean | 1.32 | 0.89 | 1.14 | 2.13 | 0.83 |
| Standard deviation | 0.65 | 0.22 | 0.40 | 0.60 | 0.26 |

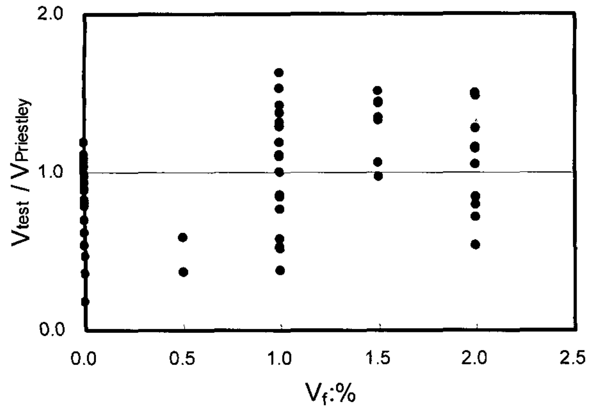
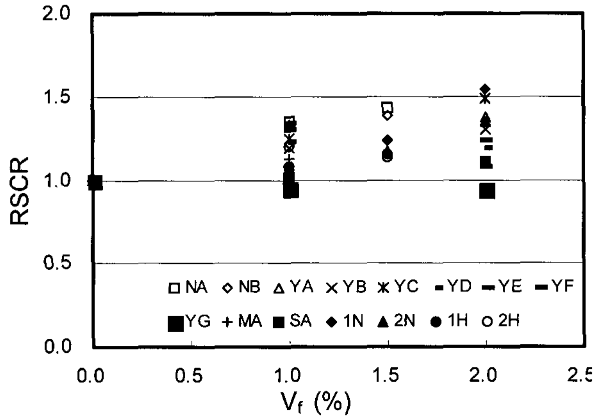
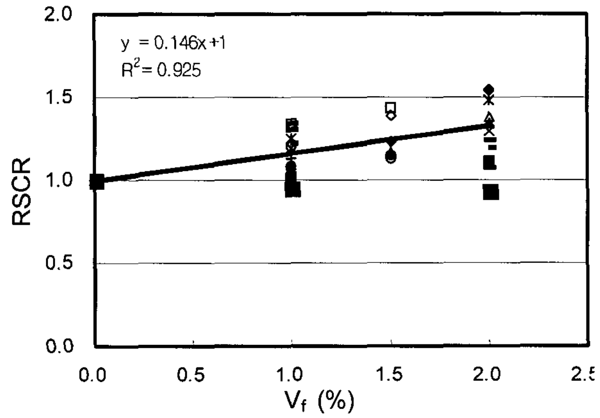



**Fig. 8** Shear strength estimation by Priestley method




(a) Relative shear capacity ratio




(b) Regression analysis for RSCR

**Fig. 9** Results of regression analysis

content increased. Mean value of $V_f$ 1.0%, 1.5% and 2.0% are 1.19, 1.24 and 1,26, respectively and standard deviations are 0.13, 0.12 and 0.19, respectively. These are very reasonable values, which are sufficient for performing regression analysis, where to results are shown in Fig. 9 (a). Results of regression analysis were shown in Fig. 9 (b).

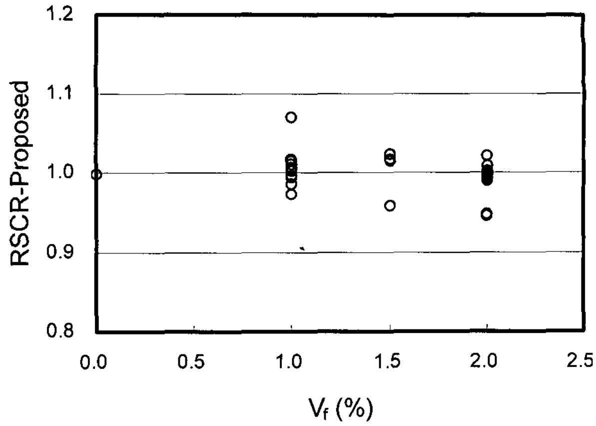



**Fig. 10** Proposed RSCR by modified Priestley

And it shows a good reliable result that has reliability index $R^2$ as 0.925. Finally, steel fiber effect in SFRC column ($V_{sf}$) is estimated as a 0.146 in percentile value for volume fraction of concrete.

To predict the shear strength of SFRC columns, Priestley equation is modified by linear add the steel fiber effect to Eq. (6), where the modified equation is shown in Eq. (7).

$$V_n = V_c + V_s + V_p + V_{sf} \tag{7}$$

$$V_c = k\sqrt{f_c'}A_e ,\quad V_p = P\tan\alpha ,\quad V_s = (A_v f_{yh} D\cot 30)/s ,$$

$$V_{sf} = 0.146 V_f$$

Plotted RSCR results by proposed Eq. (7) are shown in Fig. 10. It shows very reliable results with 0.02 standard deviation.

## 7. Conclusions

From the review of previous studies and shear strength equation, and evaluation of performance tests, following conclusion can be made:

1) Steel fiber effect of SERC columns proved to be more effective in improving strength and ductility capacity than in stiffness and energy capacity.
2) Maximum enhancement of shear strengthening effect could be achieved at approximately 1.5 % of steel fiber content for construction site application.
3) To predict the shear capacity of SFRC columns modified Priestley equation was proposed by reviewing shear strength equations and performing structural tests.
4) In future, detailed study is needed in split cylinder strength and bonding stress of SFRC.

**Table 5** Estimation of relative shear capacity ratio

| Investigator | Group | $V_f$ (%) | $F_{ck}$ (N/mm$^2$) | $\rho_w$ (%) | Section size (cm) | $V_{max}$ (kN) | SCR | RSCR |
|---|---|---|---|---|---|---|---|---|
| Nagasaka | NA | 0.0 | 30 | 0.00 | 20*20 | 92 | 1.33 | 1.00 |
| | | 1.0 | 30 | 0.00 | 20*20 | 124 | 1.79 | 1.35 |
| | | 1.5 | 30 | 0.00 | 20*20 | 132 | 1.91 | 1.44 |
| | NB | 0.0 | 30 | 0.23 | 20*20 | 124 | 1.79 | 1.00 |
| | | 1.0 | 30 | 0.23 | 20*20 | 164 | 2.37 | 1.32 |
| | | 1.5 | 30 | 0.23 | 20*20 | 172 | 2.48 | 1.39 |
| | | 2.0 | 30 | 0.23 | 20*20 | 192 | 2.77 | 1.55 |
| Yashiro | YA | 0.0 | 29 | 0.56 | 25*25 | 158 | 1.49 | 1.00 |
| | | 1.0 | 33 | 0.56 | 25*25 | 224 | 1.98 | 1.33 |
| | | 2.0 | 27 | 0.56 | 25*25 | 209 | 2.05 | 1.38 |
| | YB | 0.0 | 38 | 0.85 | 25*25 | 198 | 1.63 | 1.00 |
| | | 1.0 | 31 | 0.85 | 25*25 | 214 | 1.94 | 1.19 |
| | | 2.0 | 28 | 0.85 | 25*25 | 220 | 2.12 | 1.30 |
| | YC | 0.0 | 31 | 1.28 | 25*25 | 185 | 1.67 | 1.00 |
| | | 1.0 | 31 | 1.28 | 25*25 | 229 | 2.08 | 1.25 |
| | | 2.0 | 33 | 1.28 | 25*25 | 283 | 2.48 | 1.49 |
| | YD | 0.0 | 40 | 0.56 | 25*25 | 247 | 1.97 | 1.00 |
| | | 1.0 | 30 | 0.56 | 25*25 | 260 | 2.41 | 1.22 |
| | | 2.0 | 29 | 0.56 | 25*25 | 250 | 2.35 | 1.19 |
| | YE | 0.0 | 40 | 0.56 | 25*25 | 260 | 2.07 | 1.00 |
| | | 1.0 | 23 | 0.56 | 25*25 | 253 | 2.7 | 1.30 |
| | | 2.0 | 29 | 0.56 | 25*25 | 272 | 2.56 | 1.24 |
| | YF | 0.0 | 40 | 0.85 | 25*25 | 282 | 2.25 | 1.00 |
| | | 1.0 | 19 | 0.85 | 25*25 | 260 | 3.02 | 1.34 |
| | | 2.0 | 31 | 0.85 | 25*25 | 265 | 2.42 | 1.08 |
| | YG | 0.0 | 32 | 1.28 | 25*25 | 265 | 2.36 | 1.00 |
| | | 1.0 | 26 | 1.28 | 25*25 | 227 | 2.25 | 0.95 |
| | | 2.0 | 27 | 1.28 | 25*25 | 229 | 2.21 | 0.94 |
| Makitani | MA | 0.0 | 37 | 0.20 | 15*15 | 63 | 1.46 | 1.00 |
| | | 1.0 | 45 | 0.20 | 15*15 | 79 | 1.65 | 1.13 |
| | | 1.5 | 34 | 0.20 | 15*15 | 69 | 1.68 | 1.15 |
| Sakai | SA | 0.0 | 25 | 0.28 | 20*20 | 75 | 1.18 | 1.00 |
| | | 1.0 | 28 | 0.28 | 20*20 | 80 | 1.2 | 1.02 |
| | | 2.0 | 27 | 0.28 | 20*20 | 86 | 1.31 | 1.11 |
| This study | 1N | 0.0 | 27 | 0.26 | 30*30 | 216 | 1.46 | 1.00 |
| | | 1.0 | 27 | 0.26 | 30*30 | 228 | 1.55 | 1.06 |
| | | 1.5 | 28 | 0.26 | 30*30 | 270 | 1.80 | 1.23 |
| | | 2.0 | 25 | 0.26 | 30*30 | 322 | 2.25 | 1.54 |
| | 2N | 0.0 | 27 | 0.21 | 30*30 | 200 | 1.36 | 1.00 |
| | | 1.0 | 27 | 0.21 | 30*30 | 218 | 1.42 | 1.04 |
| | | 1.5 | 28 | 0.21 | 30*30 | 239 | 1.59 | 1.17 |
| | | 2.0 | 25 | 0.21 | 30*30 | 262 | 1.83 | 1.35 |
| HHLee[13)] | 1H | 0.0 | 44 | 0.26 | 30*30 | 329 | 1.74 | 1.00 |
| | | 1.0 | 61 | 0.26 | 30*30 | 419 | 1.88 | 1.08 |
| | | 1.5 | 61 | 0.26 | 30*30 | 444 | 2.00 | 1.15 |
| | | 2.0 | 68 | 0.26 | 30*30 | 450 | 1.92 | 1.10 |
| | 2H | 0.0 | 44 | 0.21 | 30*30 | 303 | 1.60 | 1.00 |
| | | 1.0 | 61 | 0.21 | 30*30 | 427 | 1.92 | 1.20 |
| | | 1.5 | 61 | 0.21 | 30*30 | 403 | 1.81 | 1.13 |
| | | 2.0 | 68 | 0.21 | 30*30 | 410 | 1.75 | 1.09 |

## Notation

$A_e$ effective gross section
$A_g$ gross section
$A_v$ area of shear reinforcement
b section width
$b_w$ web width
D section depth
d effective section depth
f'c compression strength of concrete
$f_y$ yield strength of reinforcement
$f_{yh}$ yield strength of shear reinforcement in Eq. (6)

| | |
|---|---|
| $j$ | length between main reinforcement in Eq. (5) |
| $j_t$ | length between main reinforcement in Eq. (3) |
| $k$ | displacement ductility |
| $M/Qd$ | shear span to depth ratio in Eq. (5) |
| $M/Vd$ | shear span to depth ratio in Eq. (3) |
| $N$ | axial force in Eq. (3) |
| $N_u$ | axial force in Eq. (2) |
| $n$ | $\frac{N}{bD\sigma_B}$ |
| $P$ | axial force in Eq. (4) |
| $p_t$ | ratio of tension reinforcement |
| $p_w$ | ratio of shear reinforcement in Eq. (3) & (5) |
| $\rho_w$ | ratio of shear reinforcement in Eq. (4) |
| $\phi$ | $\frac{p_t\sigma_y}{\sigma_B}$ |
| $s$ | spacing of shear reinforcement |
| $\sigma_0$ | ratio of axial force |
| $\sigma_B$ | compression strength of concrete in Eq. (3) & (5) |
| $\sigma_{wy}$ | yield strength of shear reinforcement in Eq. (3) & (5) |
| $\sigma_y$ | yield strength of tension reinforcement in Eq. (3) |
| $V_c$ | nominal shear strength of concrete |
| $V_f$ | steel fiber volume fraction |
| $V_n$ | nominal shear strength |
| $V_p$ | shear strength caused by axial load effect |
| $V_s$ | nominal shear strength of shear reinforcement |
| $V_{sf}$ | shear strength caused by steel fiber effect |
| $V_u$ | ultimate shear strength |

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