

EFFECTIVENESS OF STEEL FIBER REINFORCEMENT ON IMPROVING CARRYING CAPACITIES AND DEFORMATION CHARACTERISTICS OF REINFORCED CONCRETE COLUMNS

Tomoya Nagasaka (I)

SUMMARY

This paper presents the effectiveness of steel fiber as web reinforcement on the performance of reinforced concrete columns subjected to cyclic reversals of horizontal loads, in an experimental comparison of the columns reinforced with steel fibers and the conventional ones reinforced with hoops alone. It is shown from the test results that the steel fiber reinforcement is remarkably effective in increasing shear capacity, deformation capability and energy absorption capacity, and that it is more efficient than conventional web reinforcement with hoops alone.

INTRODUCTION

It is well recognized that steel fiber reinforced concrete can obtain higher tensile strength and more toughness than plain concrete. Several attempts have been made to take advantage of the preferable characteristics with the intention of improving the performance of reinforced concrete beams, and the considerable effectiveness has been reported (Refs. 1 to 9). From the aspect of cost and workability in construction, however, it is not considered advisable to use steel fibers as flexural reinforcement, in comparison with conventional reinforcing steel bars. It is expected more effective to use steel fibers as shear reinforcement or web one, because the shear failure of concrete beams should be substantially attributed to tensile failure of the concrete which could extend over the whole depth. Nevertheless, there have been reported few researches on short columns subjected to severe shear forces in this field except for some papers in Japan (Refs. 10 to 13).

To determine the effectiveness and efficiency of steel fiber reinforcement in columns subjected to cyclic reversals of horizontal loads such as seismic forces in comparison with the conventional hoop reinforcement, two series of test on columns with the same sectional properties including flexural reinforcing steel bars were carried out: one was on the columns reinforced with the steel fibers of three different contents in addition to the hoops of the same web reinforcement ratio; and the other was on the conventional ones reinforced with the hoops of two different ratios.

DESIGN OF TEST COLUMNS

The test columns were designed under condition that they were subjected to a constant vertical load and cyclic reversals of horizontal loads as shown in Fig. 1a. All the columns, 20 x 20 x 60 cm within the effective length, with rigid blocks at the top and bottom were given the same flexural reinforcement of a tension steel reinforcement ratio of 0.64 %. Steel fiber reinforced concrete columns were provided with some conventional hoops, too,

(I) Associate Professor, Faculty of Engineering, Tokai University

because without any hoop they would collapse in a brittle manner soon after reaching the maximum loading capacity. The chosen hoop ratio was 0.2 %, which corresponded to the lower limit required by "AIJ Standard for Structural Calculation of Reinforced Concrete Structures". The outline of steel fiber reinforced concrete columns is shown in Fig. 1b.

Web reinforcement types are listed in Table 1, where there were three different percentages by volume of steel fibers, 1.0, 1.5 and 1.94 %, in the steel fiber reinforced concrete columns (hereafter

called SFRC columns), and two different percentages of hoop ratio, 0.81 and 1.39 %, in the convenient reinforced concrete columns (hereafter called HPRC columns). In each type there were provided columns subjected to two different vertical loads: one was 15 t under which the axial stress of column was approximately equal to $F_c/6$, where F_c is the compressive strength of the concrete or the composite, 225 kg/cm² assumed for this experiment; and the other was 30 t under which the axial stress was approximately equal to $F_c/3$. In the former group it was expected that the tensile yielding of flexural reinforcing bars would precede the shear failure of the columns, although the shear capacity of the columns reinforced with hoops of 0.2 % alone was inferred to be only just above the flexural one. The hoop ratio calculated by equalizing the allowable shear capacity by AIJ Standard to the flexural capacity was 1.39 %, which corresponded to one of the two hoop ratios for HPRC columns shown in Table 1, and which exceeded the upper limit of 1.2 % by AIJ Standard. The objective was to examine the effectiveness of steel fiber for ensuring deformation capability of columns without some premature shear failure after flexural yielding. On the other hand, in the latter group it was expected that the shear capacity of the column with the hoops of 0.2 % alone, without any addition of web reinforcement, would be considerably lower than the flexural one. The hoop ratio calculated by equalizing the allowable shear capacity to the flexural capacity was 1.97 %, which remarkably exceeded the upper limit. The objective was to examine the effectiveness of steel fiber for ensuring shear capacity and deformation capability simultaneously under a severer condition. Additionally, it should be noticed that in each couple of SFRC 10 and HPRC 10 column and SFRC 19 and HPRC 19 column in Table 1 the content of web reinforcement was made equal in volume or weight.

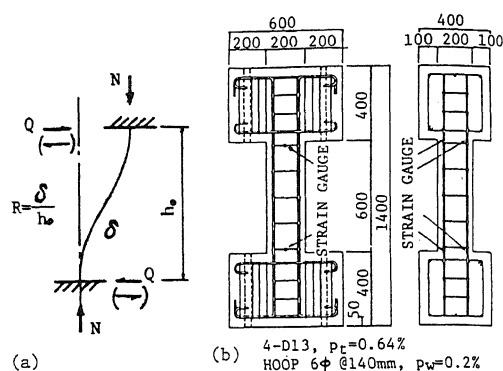


Fig. 1 Loading Condition and Outline of Steel Fiber Reinforced Concrete Columns

Table 1 Types of Web Reinforcement

Web reinforcement	Columns with steel fibers			Conventional columns	
	SFRC 10	SFRC 15	SFRC 19	HPRC 10	HPRC 19
Hoop 6φ, spacing, mm (Hoop ratio, p_w , %)	@140 (0.2)	@140 (0.2)	@140 (0.2)	@35 (0.81)	@20 (1.39)
Fiber content, V_f , % by volume	1.0	1.5	1.94	0	0
Total reinforcement content, % by volume	1.30	1.80	2.23	1.30	2.23

TEST PROGRAM

The mix proportions of the concrete or the composite are shown in Table 2, where the maximum size of the sand and gravel were 2.5 and 15 mm, respectively. Crimped fibers of 0.25 x 0.5 x 25 mm were used for the steel fiber reinforced concrete. The columns were tested at the age of 28 to 30 days.

The loading apparatus is shown in Fig. 2. Prior to horizontal loading, one of the chosen vertical loads was applied to the upper stub of column by a 40 t capacity hydraulic jack, and was held constant during cyclic horizontal loading. The horizontal loads were applied by a hydraulic jack with a capacity of 50 t for pushing and 25 t for pulling. The cyclic loading process is shown in Fig. 3. The initial displacement amplitude was 5×10^{-3} rad., which was repeated 2.5 cycles; thereafter it was increased by 5×10^{-3} rad. at every 2.5 cycles up to 30×10^{-3} rad.. Further, the amplitude was increased by 10×10^{-3} rad. at every 2.5 cycles, and the loading was continued until the column could not carry the fixed vertical load. The horizontal displacement of the top of column relative to the bottom was measured by two displacement transducers with a capacity of 200 mm equipped on the both sides of column and supplemented in a small range by two dial gauge type transducers with a capacity of 50 mm. The horizontal displacement was represented by the average of the two readings obtained from the former transducers. Visual observation for cracks and failures were made throughout the test.

TEST RESULTS AND DISCUSSION

Loading Apparatus

Table 3 shows the first flexural load, Q_{cb} , first shear crack load, Q_{cs} , maximum load, Q_{max} and mode of failure of each test column with the compressive strength, F_c and the direct tensile strength, F_t , while the mechanical

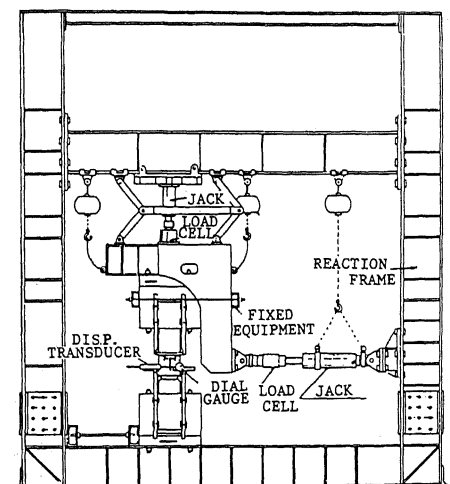


Fig. 2 Loading Apparatus

Table 2 Mixing Proportions, kg/m³

Fiber content, V_f , %	Water	Cement	Sand	Gravel	Fiber
0	274	391	978	587	0
1.0	266	380	950	570	79
1.5	265	378	945	567	118
1.94	267	376	940	564	152

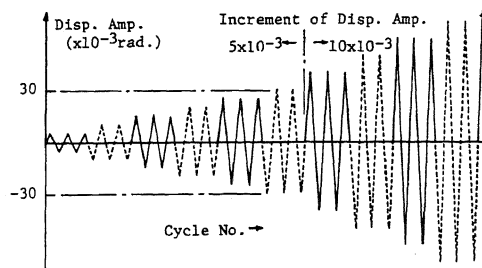


Fig. 3 Cyclic Loading Process

Table 3 Loading Capacities and Mode of Failure

Designation of column	F_c , kg/cm ²	F_t , kg/cm ²	Q_{cb} , t	Q_{cs} , t	Q_{max} , t	Mode of failure
SFRC 10-61	222	22.5	3.5	7.0	9.2	SY
SFRC 10-62	240	19.5	2.5	5.0	9.9	SY
SFRC 10-63	220	20.9	2.5	6.0	9.6	SY
SFRC 15-61	216	21.4	3.6	8.0	9.8	FY
SFRC 15-62	263	20.8	2.5	7.0	9.6	FY
SFRC 19-61	236	23.4	2.5	7.9	9.2	FY
SFRC 19-62	245	20.0	1.5	8.0	10.0	FY
SFRC 19-63	241	18.5	3.5	8.0	9.9	FY
HPRC 10-62	246	17.6	1.0	4.0	9.5	SY
HPRC 10-63	228	20.2	2.5	6.0	9.2	SY
HPRC 19-61	235	17.2	2.5	2.5	9.7	SY
HPRC 19-62	233	18.2	2.0	3.5	9.5	SY
SFRC 10-32	233	25.5	5.0	7.0	12.6	SY
SFRC 10-33	247	20.0	4.5	5.0	12.3	SY
SFRC 15-31	247	21.2	5.5	9.0	14.0	SY
SFRC 15-32	263	23.4	5.0	7.0	13.3	SY
SFRC 19-31	255	22.5	5.0	10.8	12.8	SY
SFRC 19-32	242	23.7	4.0	10.0	12.9	SY
HPRC 10-31	209	22.2	5.5	10.0	12.5	S
HPRC 10-32	231	18.3	4.5	6.0	10.0	S
HPRC 19-31	187	15.4	4.0	8.0	11.6	SY
HPRC 19-32	214	18.1	3.5	7.0	11.7	SY

S: Shear failure

SY: Shear failure after flexural yielding

FY: Flexural failure after flexural yielding

Table 4 Mechanical Properties of Reinforcing Bars, t/cm²

Type of bars	Yield strength	Max. strength	Young's modulus
D13	3.78	5.51	2110
6 ϕ	3.51	4.43	2070

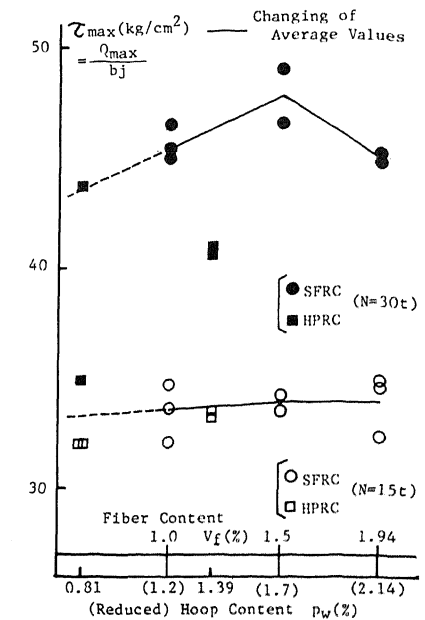


Fig. 4 Maximum Shear Stress as a Function of Fiber Content and Hoop Ratio

properties of reinforcing steel bars are shown in Table 4.

As for the first flexural crack load, no significant difference was found between SFRC columns and HPRC columns. The first shear crack load, however, shows a tendency to be higher in SFRC columns than in HPRC columns and to be significantly increased with increasing the fiber content.

Concerning the maximum load, the effect of steel fiber reinforcement was not outstandingly found under the vertical load of 15 t; but under 30 t SFRC columns obtained considerably higher values than HPRC columns and obtained the highest value at the content of 1.5 %. From the comparison of SFRC 10 with HPRC 10 and that of SFRC 19 with HPRC 19 under 30 t, it might be considered that the steel fiber reinforcement is more effective for increasing the shear capacity of the columns than the conventional reinforcement with the increase of hoops, under condition that the sum of steel fibers and hoops by volume is invariant. These tendencies are more evidently recognized in Fig. 4. This figure is a plot of the maximum shear stress, Q_{max}/b_j , as a function of the steel fiber content, V_f , and the hoop ratio, p_w , where in SFRC columns the simple algebraic sum of the fiber percentage by volume and the hoop ratio of 0.2 % was conveniently regarded as a hoop ratio (reduced hoop ratio); and "b" is the width of column and "j" is seven eighths of the effective depth of column. Further, it is observed from the figure that the increment of the maximum shear stress by the increase of the vertical load to 30 from 15 t was

about 10 kg/cm² in SFRC columns and somewhat greater than that in HPRC columns. With increasing the fiber content from 1.5 to 1.94 %, the maximum loading capacity hardly increased or decreased. Conveniently, the increase of the maximum loading capacity by adding steel fibers to the hoops of 0.2 % can be expected to be equal to or greater than that by increasing the hoop ratio numerically by the same value as the percentage by volume of the additional steel fibers.

Crack Pattern and Failure Mode

Fig. 5 illustrates the crack patterns near at the maximum load and in the ultimate state.

Near the maximum load, generally speaking, SFRC columns exhibited the characteristics of arresting cracks in width, length and number more outstandingly with increasing the fiber content, and simultaneously the crack mode approached to the flexural one; in HPRC columns all of them produced remarkable shear cracks and particularly under the vertical load of 30 t some of the cracks extended to a great extent over the whole depth even with the hoop ratio of 1.39 %. The tensile yielding of flexural reinforcing bars occurred in all of the test columns except for HPRC columns of 0.81 % under 30 t. Additionally, bond split cracks occurred in HPRC columns but not distinctly in SFRC columns.

Concerning the ultimate state, HPRC columns collapsed in a severely brittle manner following yielding of hoops across shear cracks, linking up of shear cracks with bond split ones or dowel split ones, spalling off of cover concrete accompanying buckling of flexural reinforcing bars or the combinations of them. In contrast, SFRC columns were in a more moderate manner reached the ultimate state with increasing the fiber content; under 15 t the failure mode was a flexural one except for that of SFRC columns of 1.0 %; under 30 t it was changed to a shear mode but split failure, spalling

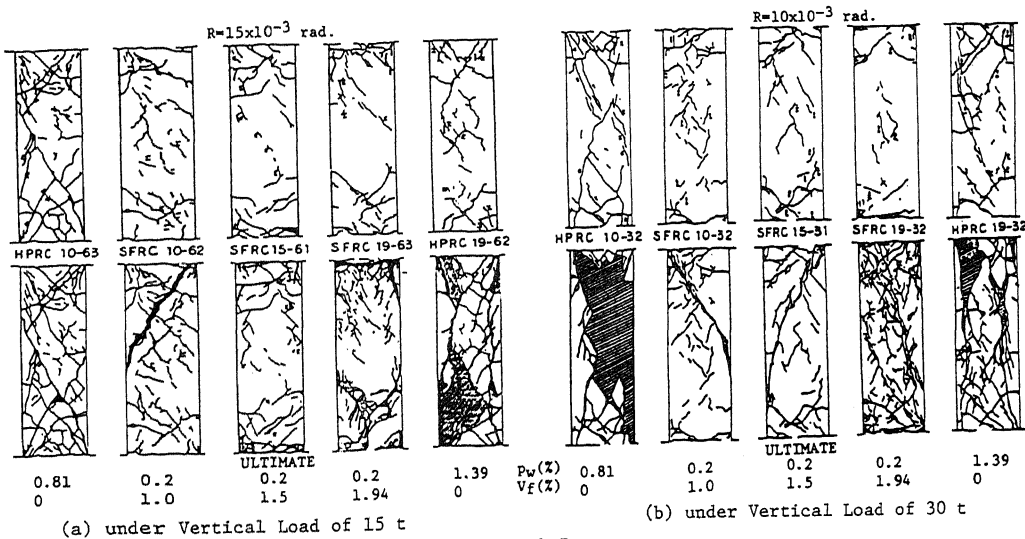


Fig. 5 Crack Pattern

off of cover concrete and buckling of reinforcing bars did not occur.

Restoring Force Characteristics

Fig. 6 shows representative load-displacement curves of the test columns. It was difficult to find some significant difference in loop shape between SFRC and HPRC columns and also to recognize the distinctive difference due to

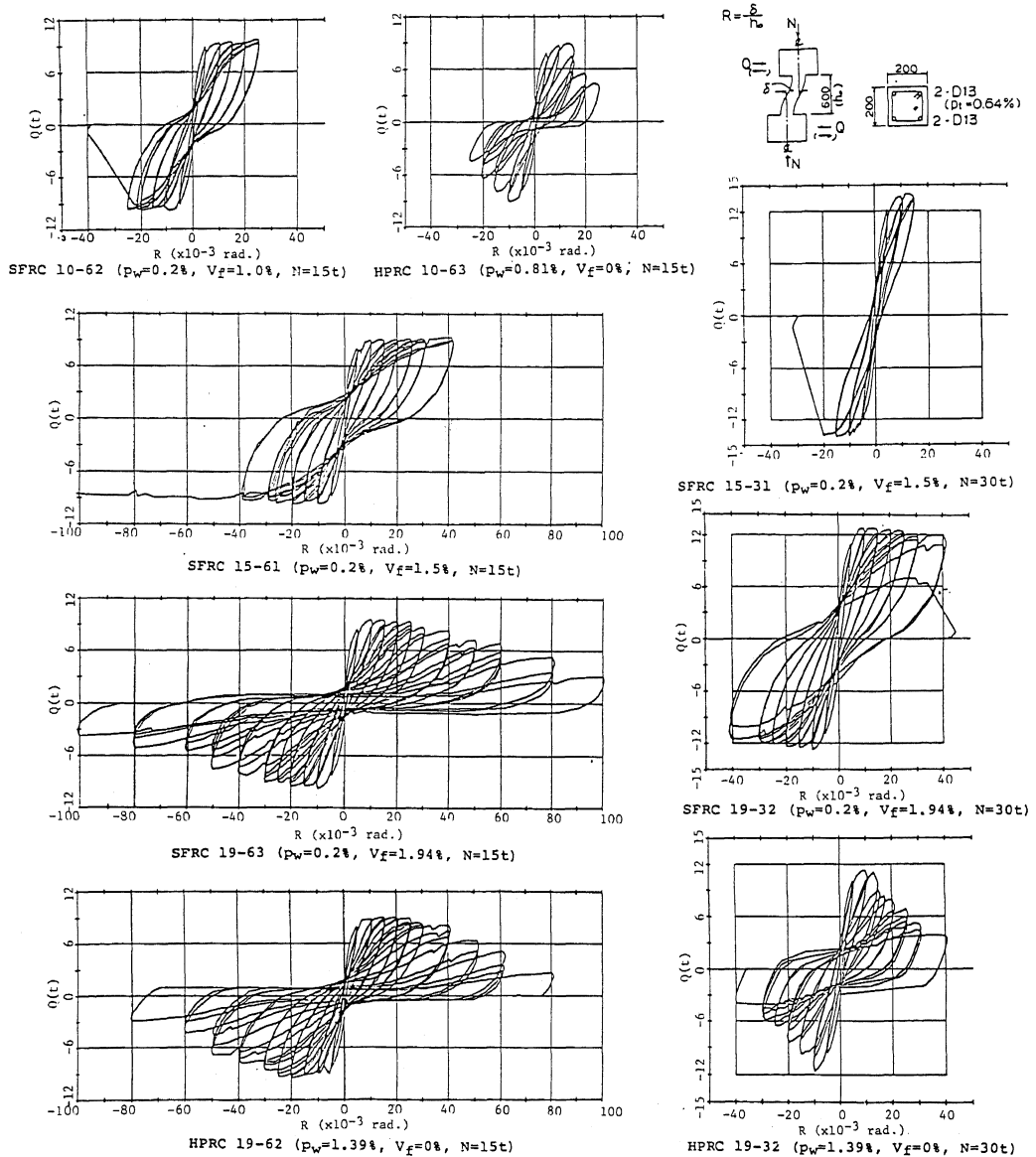


Fig. 6 Load - Displacement Curves

the fiber content in SFRC columns. From the viewpoints of deformation capability and energy absorption capacity, however, the effects due to the steel fiber reinforcement and increasing the fiber content can be obviously observed. Concerning energy absorption capacity, the tendencies can be evidently recognized from Fig. 7, which illustrates a variation of the accumulative hysteresis absorbing energy, E_{ah} , at the end of cycling in each displacement amplitude. Under the vertical load of 15 t, the HPRC columns with the hoop ratio of 1.39 % presented almost the same behaviour as the SFRC columns with the fiber content of 1.94 % up to the displacement of 30×10^{-3} rad., but thereafter remarkably reduced in load carrying capacity and finally resulted in inferior energy absorption capacity to the SFRC columns; those ones under 30 t began to reduce the load carrying capacity near at the displacement of 10×10^{-3} rad. and resulted in explicitly inferior energy absorption capacity to the SFRC columns of 1.94 % (see Fig. 6b). The SFRC columns of 1.5 % under 15 t were no way inferior to those ones of 1.94 %, but under 30 t they were remarkably inferior in maintaining the load carrying capacity against the extension of the displacement and ensuring energy absorption capacity to those ones of 1.94 %. Further, dynamic response analyses were made on one mass models simulating the hysteresis behaviours obtained from the test results, and confirmed the superiority of the SFRC columns, although the analytical results were omitted in this paper out of space consideration.

CONCLUSIONS

From the experiment on reinforced concrete short columns with hoops alone and those ones with steel fibers in addition to some hoops as web reinforcement, the following conclusions were obtained:

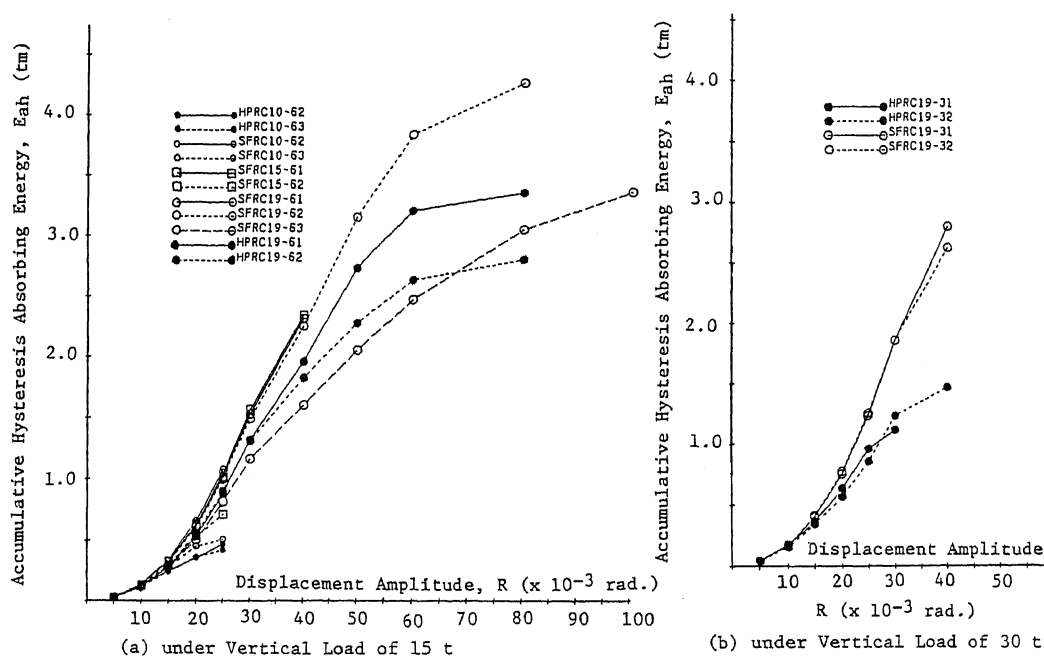


Fig. 7 Accumulative Hysteresis Absorbing Energy as Function of Displacement Amplitude

- 1) On the condition of the same content by volume of web reinforcement, steel fiber reinforcement was more effective for increasing the shear capacity and improving the restoring force characteristics than conventional ones with hoops alone, particularly when the hoops are inevitable to be congested.
- 2) The increase of shear capacity by adding steel fiber to be conventional hoops can be expected to be equal to or greater than that by increasing the hoop ratio numerically by the same value as the percentage by volume of the additional fibers.
- 3) Steel fiber reinforcement was remarkably effective for preventing brittle shear failure, split failure along flexural reinforcing bars and spalling off of cover concrete.
- 4) The steel fiber reinforced concrete columns demonstrated more deformation capability and more energy absorption capacity by increasing the fiber content than the conventional concrete columns reinforced with hoops alone.

The conclusions above should be confirmed under other conditions.

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