

# Seismic performance of New Steel Concrete Composite Beam-Columns

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## **SUMMARY:**

A steel concrete composite column consisting of recycled concrete and encased steels with square steel tube is a new structural system proposed by the authors, and is being conducted continuous and comprehensive studies to make it practical. Experimental studies on stub-column test have been carried out, and it was revealed that the AIJ (Architectural Institute of Japan) design formulas for SRC (Steel Reinforced Concrete) structures can be applied for evaluating the ultimate compressive strength of these stub-columns. However, in case of the composite columns in which recycled concrete is used, flexural behavior has not yet been clarified. Therefore, seven composite beam-columns were tested under bending load. This paper summarizes the test results and discusses how to evaluate the structural characteristics of these composite beam-columns.

*Keywords: Composite member, beam-column, flexural strength, ductility, fiber analysis*

## **1. INTRODUCTION**

A steel concrete composite column consisting of recycled concrete and encased steels with square steel tube is a new structural system proposed by the authors, and is being conducted continuous and comprehensive studies to make it practical. Experimental studies on stub-column test have been carried out, and it was revealed that the AIJ design formulas for SRC structures can be applied for evaluating the ultimate compressive strength of these stub-columns. However, in case of the composite columns in which recycled concrete is used, flexural behavior has not yet been clarified. Therefore, pure bending tests were carried out to obtain general information on the structural performance of composite beam-columns, such as their maximum strength and deformation capacity. This paper presents the results of an experimental investigation and analytical simulation of the behavior of pure bending loaded composite beam-columns.

## **2. EXPERIMENTAL INVESTIGATION**

### **2.1. Specimens and Parameters**

#### *2.1.1. Test specimens*

The details of typical specimens are shown in Figure 2.1 and Table 2.1. A total of eight specimens were tested; one steel column (specimen S), five steel concrete composite columns (specimens SC-P, CS-R, SC-F, SC-R-S2 and SC-R-S6) and two concrete filled steel tubular columns (specimens CFT-S2 and CFT-S6). All specimens except for specimen S had a 300 mm square section. The steel encased in each column had a single H-section steel of 194x150x6x9 mm. The test parameters were as follows: 1) encased steel, 2) concrete and 3) square steel tube. The square steel tubes were fabricated by welding together two pieces of channel section, which were cold-formed from flat plate.

Specimens SC-P, SC-R and SC-F were designed to examine the effect of the type of concrete on the

flexural behavior of the composite beam-columns. Normal concrete was used for the specimen SC-P, recycled concrete was used for the specimen SC-R and fiber reinforced concrete (FRC) was used for specimens SC-F (poly vinyl alcohol (PVA) fiber, mixing volume=1%). Specimens SC-R-S2 and SC-R-S6 were planned compared with influence of square steel tube. Specimens CFT-S2 and CFT-S6 were planned compared with influence of thickness of square steel tubes. Recycled concrete was also used for above four specimens.

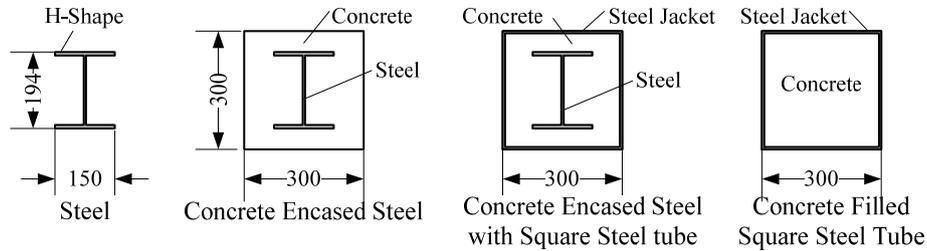


Figure 2.1. Detail of test specimens

Table 2.1. Detail of test specimens

Specimen	Inner steel	Concrete	Square tubes	Note
S		None		Steel
SC-P	H-194*150*6*9	Plane Concrete	None	Concrete Encased Steel
SC-F		Fiber Reinforced Concrete		
SC-R		Recycled Aggregate Concrete		
SC-R-S2				
SC-RS6		□-300*6.0	Concrete Encased Steel with Steel Jacket	
CFT-S2	None		□-300*2.3	Concrete Filled Steel Tube
CFT-S6			□-300*6.0	

### 2.2.2. Materials

Tables 2.2 and 2.3 provide detailed information on the material properties of the steel and concrete, respectively. The values of the material properties are the average of 3 steel coupon tensile tests or 3 concrete cylinder (100mm x 200mm) compression tests. The materials are structural steel called SS400 in Japanese Industrial Standard. Specimens with the same type concrete were filled with the same batch of Ready Mixed Concrete. The beam-column tests were carried out about one year after concrete casting. Concrete cylinders were tested on the same day as the specimens.

Table 2.2. Material properties of steel

Specimen		Grade	$t$ (mm)	$E_s$ (GPa)	$\sigma_{sy}$ (MPa)	$\sigma_{st}$ (MPa)	$\varepsilon$ (%)
H-194*150*6*9	Web	400MPa	5.87	198	365	464	26.8
	Flange		9.13	205	294	445	29.0
Steel jacket	□-300*2.3		2.18	205	241	448	39.9
	□-300*6.0		5.66	214	277	433	27.9

Note:  $\sigma_{sy}$  = yield strength,  $\sigma_{st}$  = Tensile strength,  $E_s$  = Young's modulus,  $\varepsilon$  = Elongation

Table 2.3. Material properties of concrete (material age: 1 year)

Type	$E_c$ (GPa)	$\sigma_{cB}$ (MPa)
Recycled Aggregate Concrete	30.5	53.3
Plane Concrete	37.6	45.7
Fiber Reinforced Concrete	34.5	45.3

Note:  $\sigma_{cB}$  = Compressive strength,  $E_c$  = Young's modulus

## 2.2. Experimental Procedure

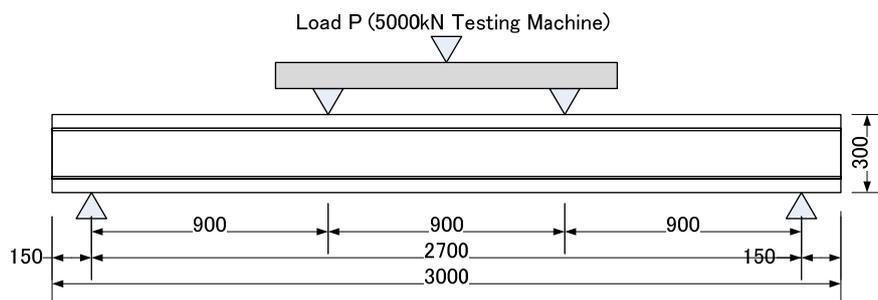
A test set-up of testing specimens subjected to bending moment is shown in Photo 2.1. The test method for beam-columns subjected to bending moment is shown in Figure 2.2. A monotonously

increasing moment was applied to the specimen by increasing the hydraulic testing machine.

Three displacement transducers were used to measure the deflections and curvatures along the test region at three points. The longitudinal and transverse strains on the built in steel and steel tube were measured by strain gauges. The deflections and strains were recorded between load applications. Local bucklings of the steel tube were marked as they were observed by the naked eye. A complete test took on an average about 45 to 60 minutes.



**Photo 2.1.** Test setup



**Figure 2.2.** Loading conditions (unit: mm)

### 2.3. Test Results

The moment-thrust-curvature relationships (referred to as  $M-\phi$  relationships) of all are shown in Figure 2.3. Each graph shows the  $M-\phi$  relationships of two or four specimens with different test variables. In Figure 2.3,  $\phi$  is an average curvature which is given by the displacement transducers. Failure modes on column faces of all specimens after loading are also presented in Photo 2.2.

Noticeable out-plane deformations were not observed in any columns. From Figure 2.3, it can be seen that all specimens showed very ductile and stable  $M-\phi$  relationships. In specimen SC-P and SC-R, cover concrete had crushed in flexure at the top of the beam-column (see Photo2.2 (a) and (b)). In specimen SC-F, the brittle failure was not significant during testing (see Figure2.3 (a)). The damage of the columns was less than that of specimen SC-P and SC-R due to the enhancement of the ductility on the concrete by the fibers (see Photo2.2 (c)). From above mentioned, the type of concrete affected the observed cracking patterns of the composite column. This indicates that the encased concrete used for FRC has a significant influence on the damage of composite columns.

In specimen of steel concrete composite column with square steel tube (SC-R-S2 and SC-R-S6), the deformation characteristic showed a stable behavior with a little strength degradation due to local

buckling after attaining the maximum capacity (see Figure 2.3 (b), Photo 2.2 (d) and (e)). However, this reduction was not very large, and in this case, the load increased again even after local buckling occurred in the steel tube.

Concrete filled steel tube (CFT) specimens (CFT-S2, CFT-S6) no drastic strength reduction was observed (see Figure 2.3 (c)). As revealed by comparing the M- $\phi$  relationships and damage situations of these specimens, the steel tubes contributed to improve the structural performance and reduce the damage in composite columns (see Photo 2.2 (f) and (g)).

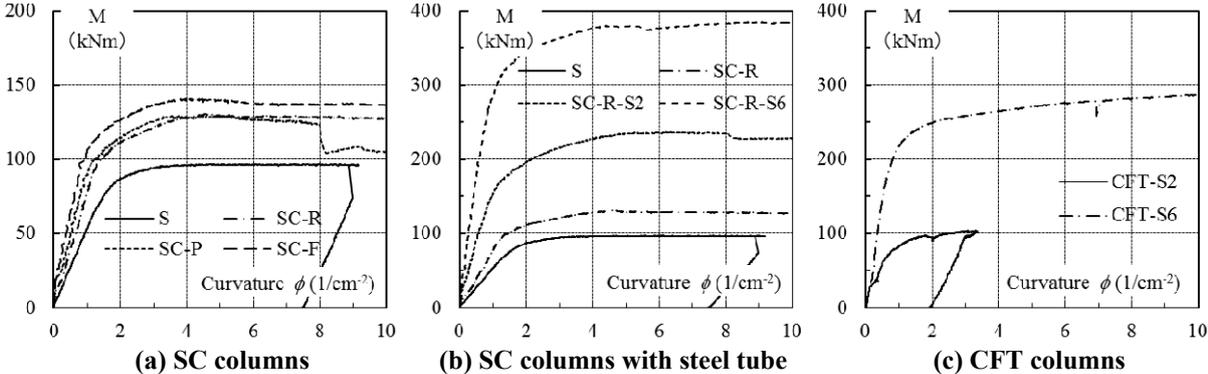


Figure 2.3. Moment-curvature relationships

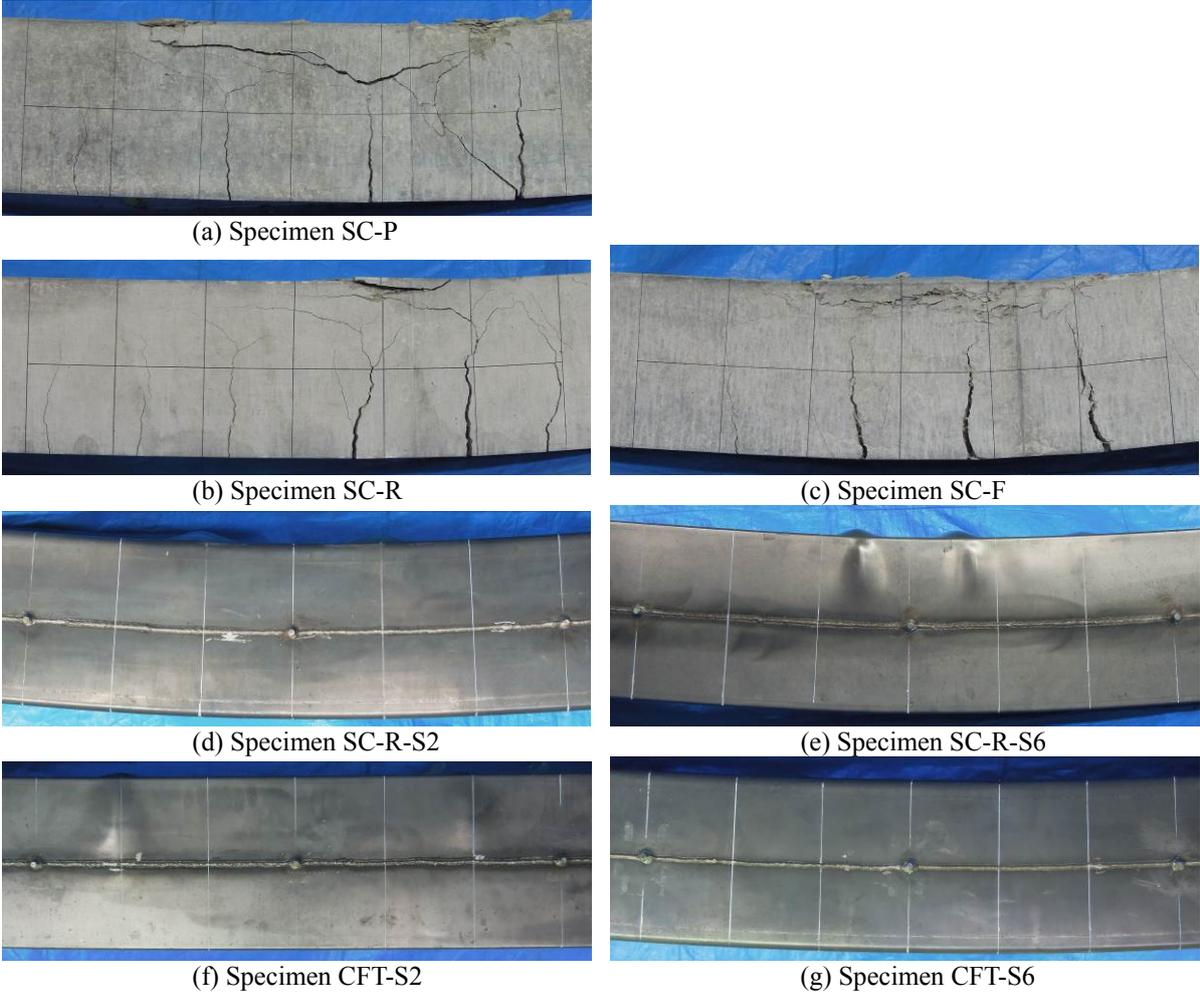


Photo 2.2. Failure pattern of specimens after loading

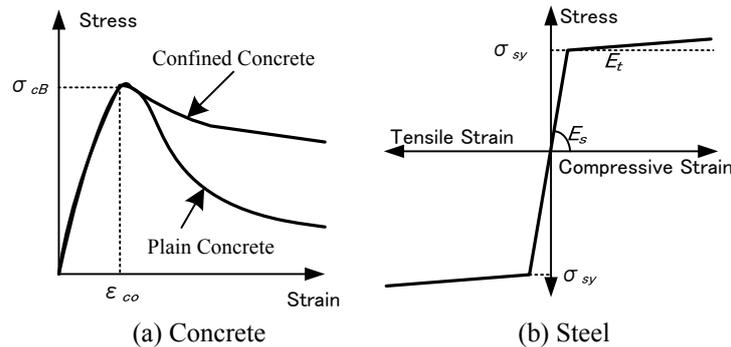
### 3. ANALYTICAL INVESTIGATION

#### 3.1. Moment-Thrust-Curvature Relationships (Comparison between Theoretical and Experimental Results)

##### 3.1.1. Stress-strain approximations

The moment-thrust-curvature relationships ( $M-\phi$  relationships) of the composite columns were numerically derived using the fiber analysis method. The stress-strain relationships of the concrete used in the analysis are shown schematically in Figure 3.1(a). As shown in Figure 3.1(a), a two-parameter model is used, in which the stress-strain curve can be determined if the models of plain (unconfined) and confined concrete are given. In specimen SC-R-S2, SC-R-S6, CFT-S2 and CFT-S6, the confining effects of the square steel tubes are considered only the improved behavior after maximum strength, based on the results of research by Fujimoto et al. (Fujimoto et al., 2004). On the other hand, plain concrete model was used for specimens SC-P, SC-R and SC-F. Here, the tensile strength of the concrete was ignored for all specimens.

The stress-strain relationships of the encased steel and square steel tubes used in the analysis are also shown schematically in Figure 3.1(b). The compressive and tensile yield stress was applied to  $\sigma_{sy}$ , where  $\sigma_{sy}$  denotes the yield stress obtained from the material coupon tests (see Table 2.2). The stress-strain relationship was assumed to be bi-linear, considering the strain-hardening effect shown in Figure 3.1(b). The stiffness  $E_t$  in the figure was determined based on the results of the coupon tests of the steel. Strength deterioration caused by local buckling of the steel is not taken into consideration in this analysis.



**Figure 3.1.** Stress-strain relationships of materials

##### 3.1.2. Moment-thrust-curvature relationships

The  $M-\phi$  relationships were obtained by assuming the following assumptions.

- There is no slip between the encased steel, concrete and square steel tube, and plane sections remain plane after bending.
- Each longitudinal fiber of steel and concrete follows the idealized stress-strain relationships discussed in the preceding section.
- Stress-strain relationships are assumed to be reversible.
- Tensile strength of the concrete is neglected.

Figures 3.2 show a comparison between the  $M-\phi$  relationships obtained from the tests (solid line) and the analysis of the all specimens. In Figure 3.2, it is observed that the initial theoretical elastic stiffness agrees with the test results for the all specimens except for specimen SC-R. Generally, the analysis reproduces the experimental behavior well regardless of the test variables.

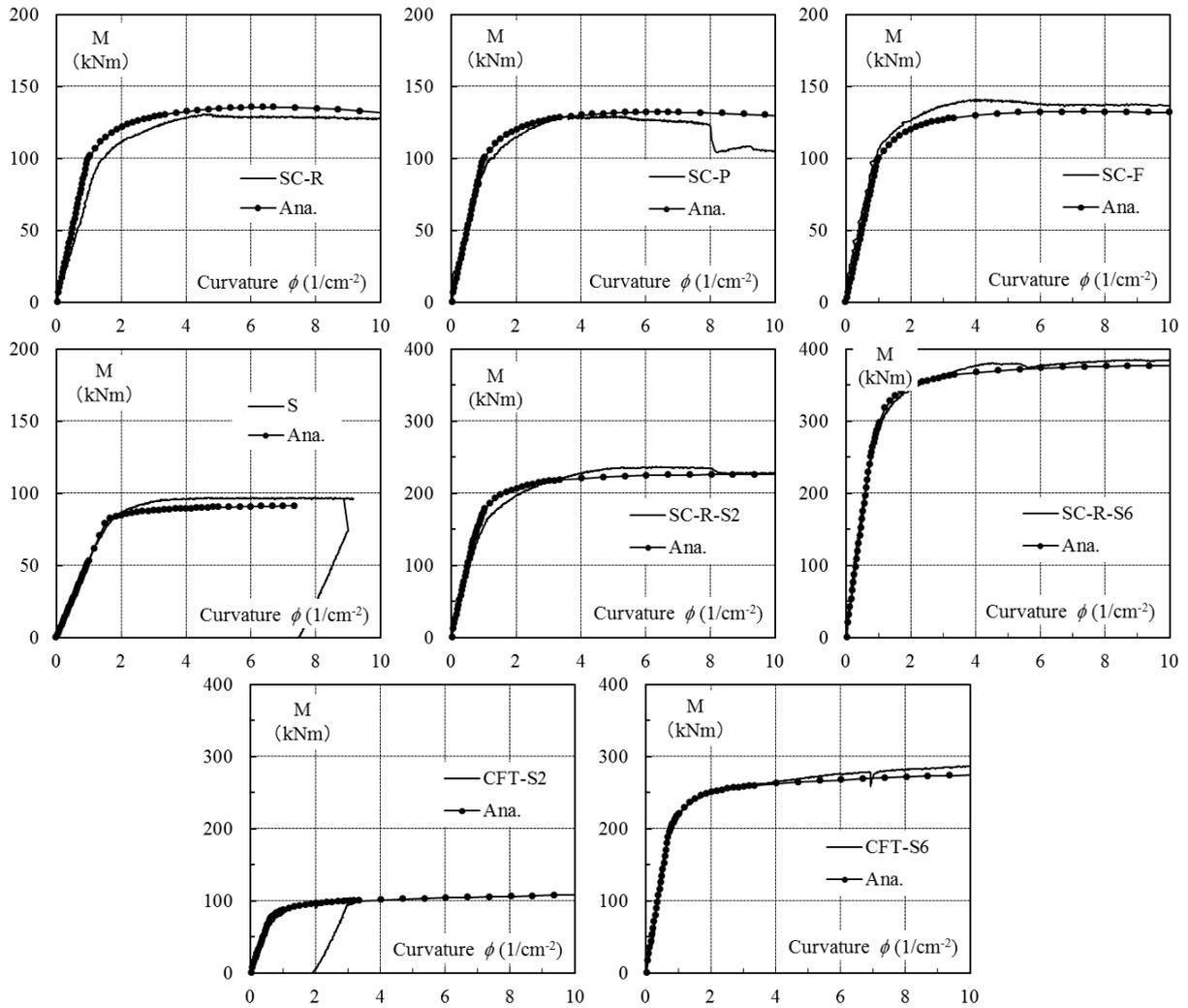


Figure 3.2. Comparison between test and fiber analysis

### 3.2. Ultimate Bending Strength

In this section a simpler estimation method which is able to predict the ultimate moment is proposed. Table 3.1 shows the values of ultimate moment of the test  $M_{exp}$ , averaged curvature at the ultimate moment of the test  $\phi_{mu}$ , and calculated ultimate moments  $M_{cal}$ . The flexural strength,  $M_{cal}$  was calculated by the superposition method (AIJ 2001). It was calculated from the rectangular stress blocks assumed for both steel and concrete, as shown in Figure 3.3. Here, concrete strength was reduced by strength reduction factor  $r_u$ . The effect of confinement on concrete strength and of local buckling of the square steel tubes was not considered.

The maximum strengths of all specimens except for specimen SC-R indicated larger than the calculated flexural strength  $M_{cal}$ . The experimental strength of specimen SC-F using FRC is 1.11 times the calculated flexural strength. This means that it is necessary to consider the effect of strength enhancement using FRC in estimating the flexural strength of SC-F columns. It is understood that the experimental flexural strengths fairly agreed with the calculated strengths.

From above mentioned,  $M_u$  of the columns subjected to increasing uniform bending moment can be estimated accurately by the simple method.

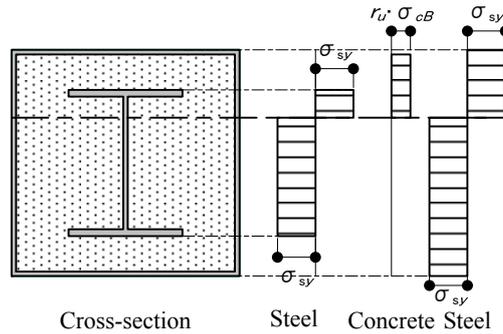
**Table 3.1.** Results of test and analysis

Specimen	$M_{exp}$ (kN·m)	$\phi_{mu}$ (1/cm*10 <sup>-2</sup> )	$M_{cal}$ (kN·m)	$M_{exp}/M_{cal}$
S	97.1	5.54	90.4	1.07
SC-P	130.8	4.65	127.4	1.03
SC-F	141.0	4.44	127.2	1.11
SC-R	129.5	3.56	130.4	0.99
SC-R-S2	238.3	22.74	217.1	1.10
SC-RS6	397.5	19.82	363.8	1.09
CFT-S2	104.1	3.31	100.0	1.04
CFT-S6	290.3	13.09	258.5	1.12

$M_{uexp}$ =Experimental ultimate moment

$\phi_{mu}$ =Average curvature at the experimental maximum moment

$M_{ucal}$ =Theoretical ultimate moment

**Figure 3.3.** Assumed stress blocks

#### 4. CONCLUSIONS

In order to investigate the structural performance of new composite beam-columns, seven composite beam-columns and one steel beam-column were tested under monotonic bending load. From the tests, the following conclusions were obtained.

- 1) The ultimate moment and the elasto-plastic behavior of the composite beam-columns subjected to increasing uniform bending moment have been clarified.
- 2) Behavior of the specimen whose steel concrete composite column using normal concrete and recycled concrete: crushes were observed on the cover concrete.
- 3) Behavior of the specimen whose steel concrete composite column using FRC: this specimen had excellent flexural behavior without severe damage, even at large deformation capacity. Using FRC for composite columns, the ductility is improved and the damage of cover concrete is reduced.
- 4) Behavior of the specimen whose steel concrete composite columns with square steel tube: these specimens had also excellent seismic behavior without severe damage, even at large deformation capacity. Using steel tube for composite columns, the ductility is improved and the damage of concrete is reduced.
- 5) Behavior of the specimen whose concrete filled square steel tubular columns: The width-to-thickness ratio,  $B/t$ , of steel tube had a significant effect on an inelastic behavior.
- 6) The AIJ design formulas for SRC structures (AIJ 2001) can applied for evaluating the ultimate flexural strengths of composite columns. The ultimate moment which is an important quantity for structural design can be estimated accurately by the proposed simple method for the columns in which recycled aggregate concrete used.
- 7) Fiber analysis was also conducted. The fiber analysis reproduced the flexural behavior of the composite beam-columns with a reasonable level of accuracy.

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