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An Experimental Study on the Effect of Steel Fiber Reinforced Concrete on the Behavior of the Exterior Beam-Column Joints Subjected to Reversal Cyclic Loading

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Abstract

For the ductile behavior of beam-column joints, closely spaced transverse reinforcement is required by earthquake codes. However, placement of this reinforcement in joints always causes some difficulties due to a lack of qualified workmanship. Therefore, it is generally observed that they are not laidout according to the design drawings. Specimens # 1 and # 2 were produced to understand the importance of closely spaced stirrups in joints. Furthermore, the use of steel fiber reinforced concrete in joints was intended to minimize the difficulties and Specimens # 3 and # 4 were produced. These four full scale specimens were tested under reversed cyclic loading. The results of the experiments were evaluated with respect to strength, damage and energy absorption. According to these evaluations, it is shown that the usage of steel fiber reinforced concrete in beam-column joints can be an alternative solution for minimizing the density of transverse reinforcement.

Key words: Beam-column joint, Steel fiber reinforced concrete, Ductile behavior

Introduction

The recent Kocaeli and Düzce earthquakes in 1999 revealed once more the importance of the design of reinforced concrete (RC) structures with ductile behavior. Ductility can be described as the ability of reinforced concrete cross sections, elements and structures to absorb the large energy released during earthquakes without losing their strength under large amplitude and reversible deformations (Hasgür and Gündüz, 1996). Generally, the beam-column joints of a RC frame structure subjected to cyclic loads such as earthquakes experience large internal forces. Consequently, the ductile behavior of RC structures dominantly depends on the reinforcement detailing of the beam-column joints. Numerous investigations have been reported about the behavior and reinforcement detailing of beam-column joints under reversed cyclic loading. Some of these include Pessiki (1990), Kurose *et al.* (1988), Kitayama *et al.* (1991), Aoyama (1985), Fuji and Morita (1991), Paulay *et al.* (1989), and Paulay (1989). In these papers, factors affecting the behavior of RC beam-column joints were studied. In brief, the results of these investigations showed that the shear strength and ductility of RC beam-column joints increased as the compressive strength of concrete and the amount of transverse reinforcement increased. Moreover, for adequate ductility of beam-column joints, the use of closely spaced hoops as transverse reinforcement was recommended in various earthquake codes for RC structures. Confining the concrete closely spaced hoop reinforcement increased not only the ductility of the concrete section at beam-column joints but also the strength of these sections. On the other hand, the cross sections of beams and columns close to the joints in RC structures under the effect of strong earthquake motion were subjected to large bending moments and shear forces. Consequently, the large amount of longitudinal and transverse reinforcements of beams and columns showed pass through these joints. However, it is tedious to install the transverse reinforcement and then cast concrete into this section considering also the congestion created by the longitudinal reinforcement passing through beam-column joints. Because of placement difficulties, the beam-column joints of RC structures can not be fully controlled by civil engineers and it is not easy to handle this situation with care according to the design drawings. Numerous researchess have attempted to reduce the workmanship difficulties by simplifying the reinforcement lay-out in the joints. In several experimental investigations (Recommendations ACI-ASCE Committee 352, 1985; Jindal and Hasan, 1984; Craig *et al.*, 1984; Katzensteiner *et al.*, 1992; Filiatrault *et al.*, 1994; Filiatrault *et al.*, 1995), the use of steel fiber reinforced concrete (SFRC) was proposed as additional reinforcement instead of squeezing stirrups in the beam-column joints. In many of these investigations, SFRC was used in certain parts of the joints together with normally spaced transverse reinforcement instead of squeezed stirrups. The effects of various parameters on the behavior of joints have been studied experimentally, such as the type of loading, the amount of steel fiber in concrete mix, the method of loading, and the amount of transverse and longitudinal reinforcements. These experiments showed that beam-column joint specimens with normally spaced stirrups and SFRC at the joints displayed higher capacity for shear forces and bending moments, dissipated more energy and showed more ductile behavior than conventional ductile beam-column joints of plain concrete.

Research Objective

This paper reports experimental study carried out to investigate the behavior of joint made of SFRC. In previous experimental investigations, the amount of the steel fiber, spacing of transverse reinforcement, type and aspect ratio of fiber and loading, application points of the cyclic loads, the scale of specimens have been separately taken into consideration as experimental parameters. In the present study, four specimens representing an exterior beam-column joint subjected to reversed cyclic loading were tested under displacement controlled loading (Figure 1). Specimens # 1 and # 2 were completely composed of plain concrete while the joint and the confinement zones of the beam and the column of Specimens # 3 and # 4 were cast with SFRC. However, all of the seismic code requirements at these zones related to the spacing of transverse reinforcement were ignored. In Specimen # 1 the requirements of the Turkish Earthquake Code regarding the spacing of stirrups were followed, whereas Specimen # 2 did not have any stirrups in the beam-column connection zone, although it satisfied all the other requirements of the code. Only one stirrup was placed into the beam-column connection of Specimen # 3; the beam-column connection of Specimen # 4 did not have any stirrup. The results obtained from the tests of both SFRC and plain concrete specimens were compared in terms of the amounts of accumulated, dissipated and stored energy, as well as damage during the tests.

Material Properties and Concrete Mixes

Two different ready-mixed concrete mixture designs were used and they are given in Table 1. The laboratory test results of the concrete cylinders revealed that the average compressive strength of the plain concrete and SFRC varited between 26 MPa and 33 MPa and between 22 MPa and 26 MPa, respectively. The yield strength of the transverse and longitudinal ribbed reinforcement was found to be 500 MPa from the tension tests performed in the laboratory. The collated hooked-end steel fibers having a length of 60mm and a diameter of 0.8mm and thus an aspect ratio of 75 with a yield strength of 1100 MPa were added into the plain concrete mix at a 1% volume ratio. As is well known, the addition of steel fibers of higher volume fractions into concrete mix makes the workability of concrete difficult. Therefore, superplasticizer was added to the concrete mix and the maximum size of coarse aggregate was limited to 10 mm for maintaining the strength and workability of the concrete.

Experimental Setup and Testing Procedure

The geometry of the specimens is given in Figure 2. The tests were carried out in the Structure & Earthquake Laboratory of Civil Engineering Faculty of İstanbul Technical University. The steel formwork was horizontally placed on the laboratory floor and the concrete was cast into this formwork while trying to avoid the mixing of plain concrete and SFRC. However, through vibration was applied after casting so that the concrete was compacted properly and no segregation took place. In the experimental setup, the test assembly was placed at the loading frame with the column horizontal and the beam vertical. Both ends of the column were arranged to be simply supported to simulate inflection points of the columns at the mid-storey. Reversed cyclic loading was applied to the end of the beam by displacement control.

Table 1. Characteristics of the concrete mixtures.

Materials	Unit	Plain concrete	SFRC
Cement	kg/m^3	340	340
Aggregate-1(10mm)	kg/m^3	906	906
Sand	kg/m^3	349	349
Water	kg/m^3	197	197
Superplasticizer	ml/m^3	5000	5000
Steel fiber 60/0.8	kg/m^3		78

The general arrangement of the experimental setup and the locations of the displacement transducers are shown in Figure 2. An axial compressive load of 150 kN was applied to the column to represent normal force.

The displacement transducers (LVDT) were placed at 15 different points on each specimen and on the loading frame to measure the deformations and displacements of the beam-column joint under the reversed cyclic load shown in Figure 3.

At each displacement level, the first three-cyclic load was applied once at the tip of the beam until the occurrence of the first residual displacement. After that residual displacement level, at each displacement level, the load was reverse cycled three times at each loading step up to the failure of the specimen. The loading steps for the test specimens and the number of loading cycles on the specimens are given in Figure 3.

For each loading cycle, the displacements at the tip of the beam were recorded on a personal computer until the target displacement level was reached.

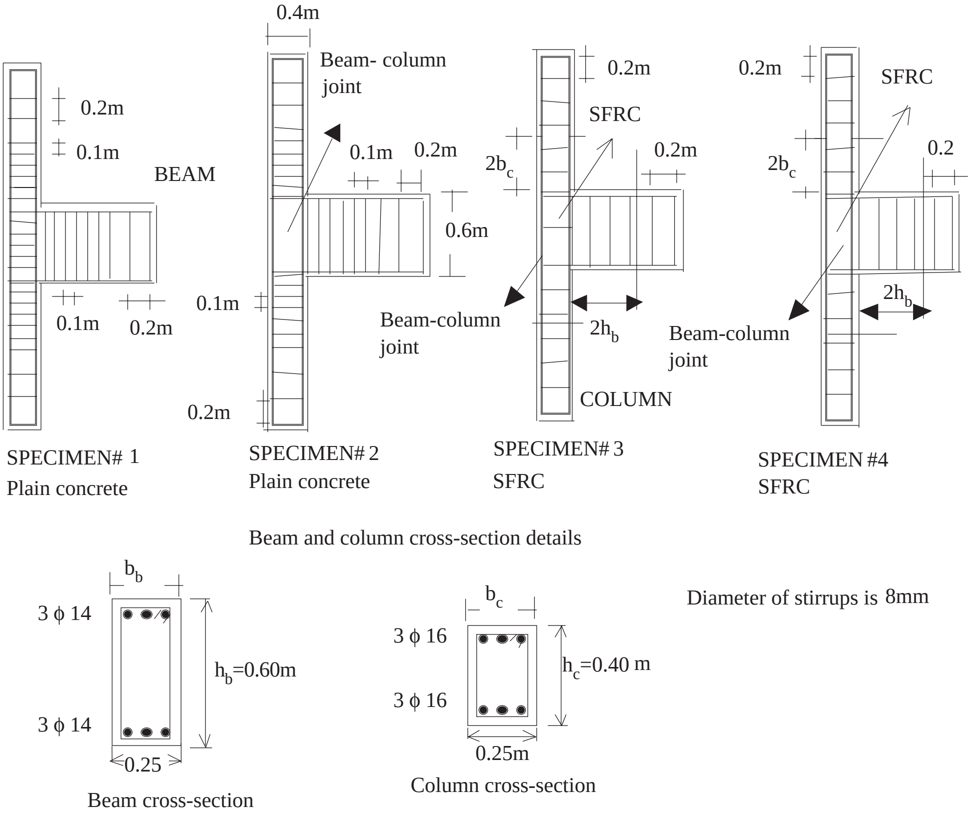


Figure 1. Details of the test specimens.

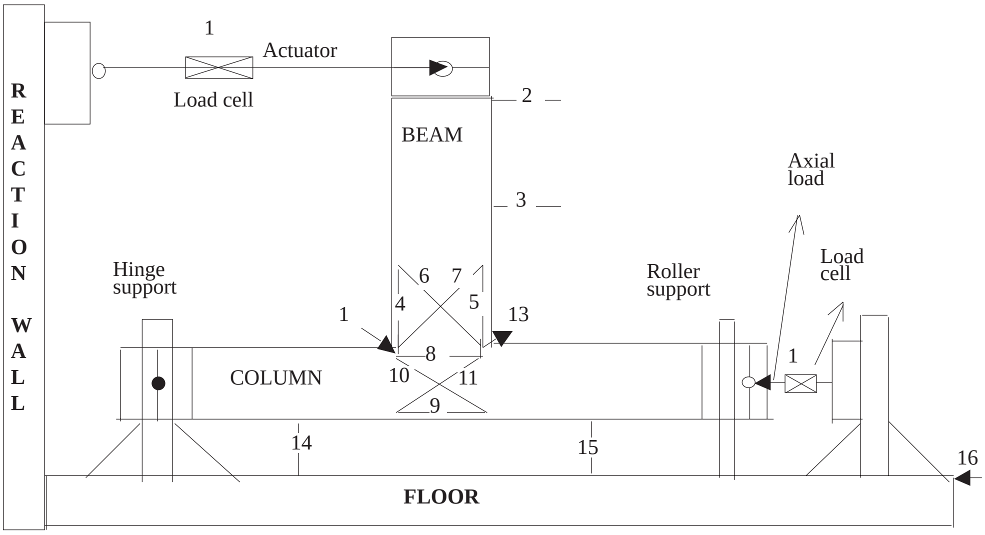


Figure 2. The general arrangement of the experimental setup and the beam tip displacement transducers (from 2 to 16).

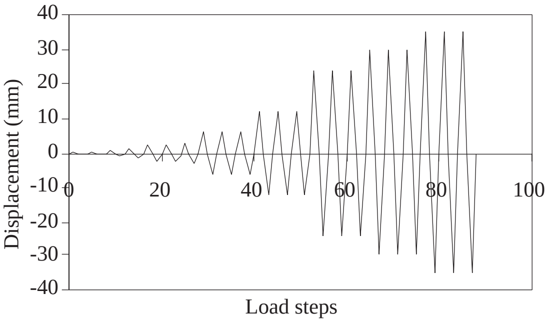


Figure 3. Displacement controlled cyclic loading.

Experimental Results

General behavior and failure mechanism

Experimental results are evaluated in relation to the behavior of joints. Although numerous quantities were measured, only the main parameters of the results are given and discussed below.

Figure 4 illustrates the load-displacement hysteresis loops measured at the tip of the beam subjected to the reversed cyclic loading applied as shown in the experimental setup. When these figures are studied, it is observed that except for Specimen # 2, all of the specimens responded to the reversed cyclic loads at a tip displacement level of 35 mm, whereas Specimen # 2 reached the failure mode at the third cycle at a displacement level equal to 30 mm. However, at the same displacement level, Specimens # 3 and # 4 experienced higher loads than the other specimens. According to these evaluations, it is seen that SFRC used in the critical regions of beam-column joints increased the strength capacity for bending moment and shear forces.

The behavior of all beam-column connection specimens tested under the reversed cyclic loading applied at the tip of the beam was similar and bending type cracks propagated depending on the load level (Figure 5). However, except for Specimen # 1 (Figure 5a), × cracks occurred in the region of the beam-column joint, since adequate transverse reinforcements had not been placed at the joints of Specimens # 2, # 3 and # 4 according to the requirements of Turkish Earthquake Resistance Code. On the other hand, × type (shear) cracks occurred at lower displacement levels in Specimen # 2 (Figure 5b) having plain concrete than in the specimens having SFRC (Figures 5c, d). Furthermore, the width of the × shear cracks in Specimen # 2 having plain concrete was larger than those of other specimens having SFRC, as expected. The use of SFRC could not prevent the occurrence of the two sided × type (shear) cracks in the region of the beam-column joint at the end of the tests. However, in the specimens in which SFRC had been used, it was observed that the widths of shear cracks were less than in Specimen # 2. As is well known, steel fibers prevent cross bending or shear cracks and they decrease the width of the cracks by bridging between two sides of cracks and furthermore, SFRC increases the shear capacity of the concrete section. Consequently, SFRC can be used partly in place of transverse reinforcements. In other words, the use of SFRC together with only one stirrup in the beam-column joint is not adequate to prevent the occurrence of shear cracks. Therefore, it can be proposed that SFRC be used together with normally spaced stirrups so that no × type shear cracks occur in beam-column joints under reversed cyclic loading. The widths and locations of cracks in the specimens at different displacement levels are given in Table 2.

Energy capacity

According to the definition of ductility in Section 1, it is aimed to determine the most ductile one among the specimens tested by taking into account the amount of total energy absorbed by beam-column joint assemblies under reversed cyclic loading. So as a measure of ductility, energy absorption capacities of the specimens were evaluated and compared. The amount of accumulated hysteretic energy of a beam-column connection subjected to reversed cyclic loading was calculated as the area under the peak value of the beam tip force-displacement hysteresis loop up to the related displacement level as given in Equation 1.

$$W_i = \int_{-\delta_i}^{\delta_i} P(x)dx + \int_{-\delta_i}^{\delta_j} P(x)dx \tag{1}$$

$$W = \sum_{i=1}^{n} W_i \tag{2}$$

where $W, W_i, P(x)\delta_i$ are total energy absorbed by each specimen, accumulated hysteretic energy, peak load and displacement at the i^{th} cycle, respectively.

At the end of the tests, total energy was calculated as the summation of the amounts of accumulated energy determined for each cycle as given in Equation 2. On the other hand, the amount of total energy was determined as the sum of the amounts of dissipated and stored energies of the beam-column joint specimens. The algorithm used in the evaluation of the accumulated hysteretic energy is shown in Figure 6 for a beam tip load-displacement hysteresis loop model.

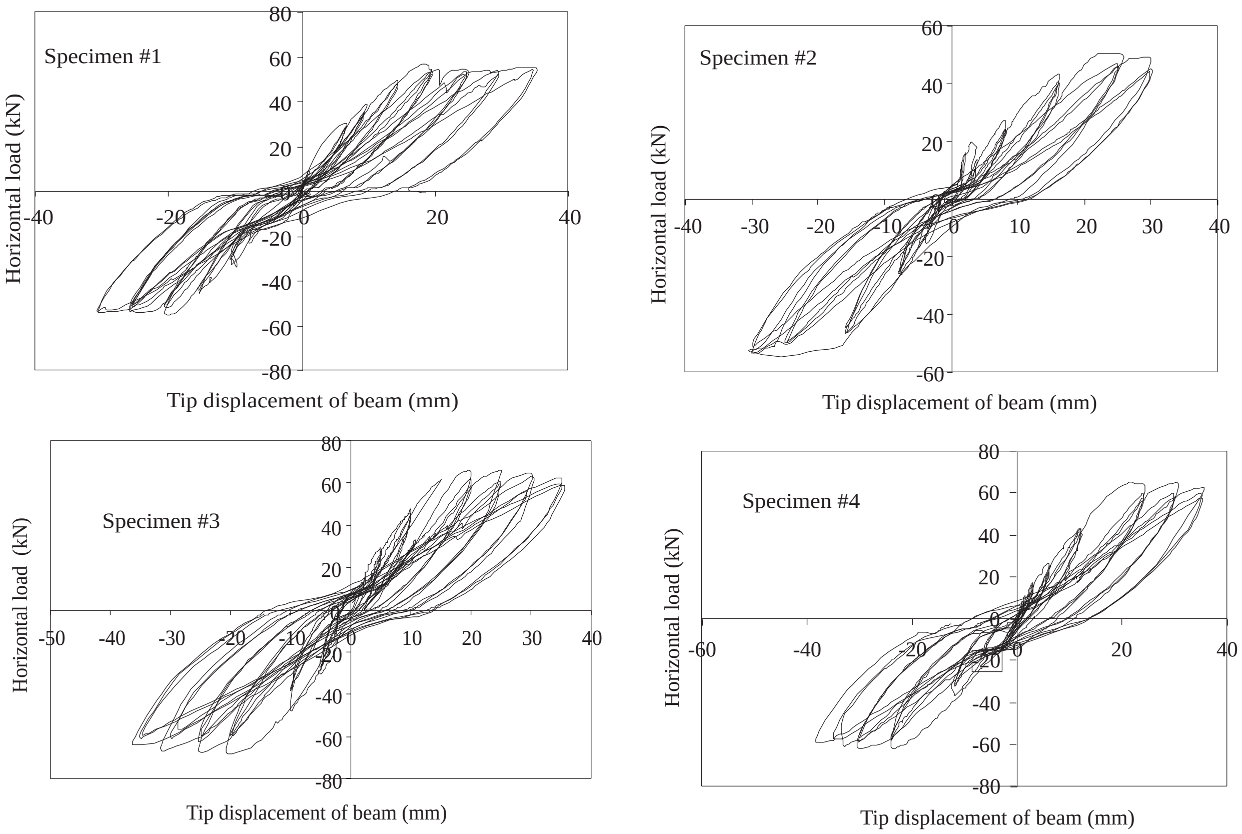
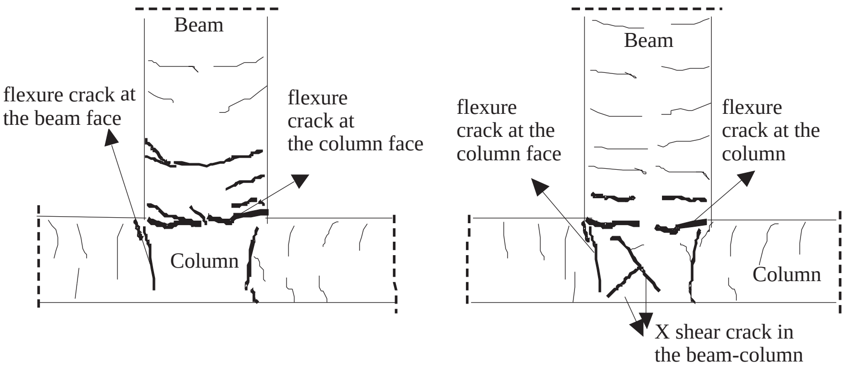
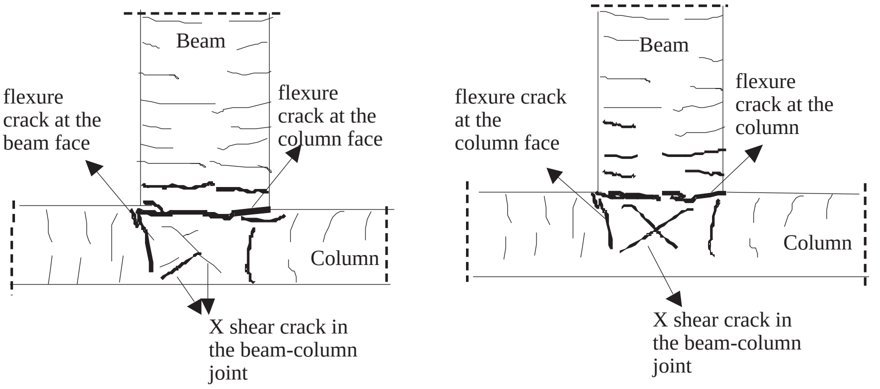


Figure 4. The horizontal load – the tip displacements of beam hysteresis loops of the beam for the specimens.



(a)
Specimen #1

(b)
Specimen #2



(c)
Specimen #3

(d)
Specimen #4

Figure 5. Crack propagation of the specimens in the confinement regions of the beam and column.

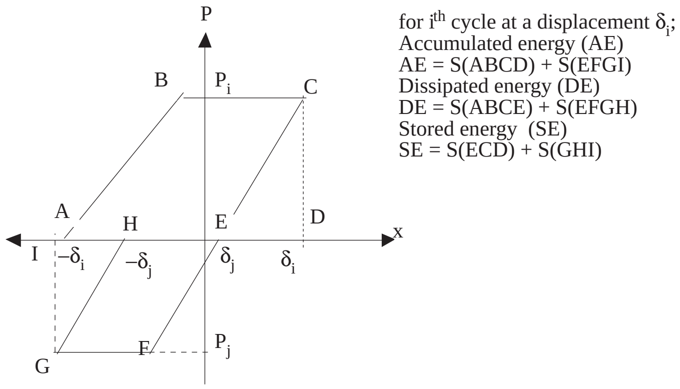


Figure 6. The algorithm for the evaluation of the energy for a beam tip load-displacement hysteresis loop model.

To study the strength and ductility of the beam-column joint specimens with either decreasing or non-decreasing situation within three cycles, the accumulated hysteretic energy absorbed by the beam-column joint up to the related displacement level for each cycle and the displacement level were evaluated numerically. Moreover, for illustrating the plastic behavior of the beam-column joint specimens subjected to reversed cyclic loading, the amount of dissipated energy for each specimen was obtained at the end of the tests. Additionally, to evaluate the strength capacity of the beam-column joint specimens at the end of the tests, the stored energy by the elastic behavior of specimens during loading was calculated. The accumulated, dissipated and stored energies within a loop of the load-displacement hysteresis were determined for each displacement level of the beam tip as given in Figure 6.

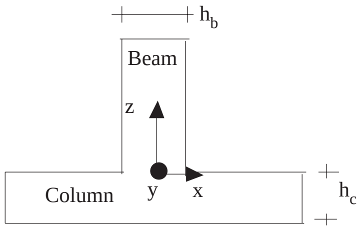
The total and accumulated energy The variation in the accumulated hysteretic energy was calculated up to the related displacement level for each peak displacement level of beam tip force-displacement hysteresis loops and is shown in Figure

Table 2. Crack widths and locations of the beam-column connection specimens at different displacement levels.

Specimen	Crack Location (m)	Bending cracks				Shear cracks				
		Beam(z)/Column(x)				Beam(z)/Column(x)				
	Displ.level (mm)	0~5	5~15	15~30	30~35	0~5	5~15	15~30	30~35	
# 1	z = 0	0.2	0.5	5.0 12.0[*]						T
	$0 < z < h_b/2$	0.1	0.3	2.0	3.0					h
	$x = hb/2$		0.2	1.0	1.5					e
	$h_b/2 < x < h_b/2$									
# 2	z = 0	0.3	1.2	10.0						C
	$0 < z < h_b/2$	0.2	0.5	3.0						r
	$x = +h_b/2$		0.2	3.0						a
	$h_b/2 < x < h_b/2$						0.1	2.0		c
# 3	z = 0	0.2	0.5	2.5/4.0[**]	3.5/7.0[**]					k
	$0 < z < h_b/2$	0.1	0.3	0.5	0.8					
	$x = +h_b/2$		0.1	1.0	2.0					W
	$h_b/2 < x < h_b/2$							0.2	0.5	i
# 4	z = 0	0.2	0.5	3	3/10[**]					d
	$0 < z < h_b/2$	0.1	0.2	1.0	1.0					t
	$x = +h_b/2$		0.1	1.2	2.0					h
	$h_b/2 < x < h_b/2$							0.1	0.2	(mm)

[*] The concrete cover snapped from the corner of the beam-column joint.

[**] Because of the position of steel fibers in the crack section, the width of crack at the two sides of the section is different. Crack width at the front and crack width at the behind, respectively.



7 for each specimen. For Specimen # 1, the tip displacement of the beam reached 35 mm after two loading cycles, but the third and last cycle was completed at a displacement level of 30 mm. This indicated the softening behavior of the specimen. In the first and second loading cycles of Specimen # 1, the accumulated energy increased as the displacement became larger. In Specimens # 3 and # 4, which are made of SFRC in the joint and confinement regions of the beam and the column, three cycles were completed at a displacement level of 35 mm. Similarly, each accumulated energy displayed an increasing trend along the displacement level, and the amounts of accumulated energy for each specimen were similar at the end of three cycles. This showed that the use of SFRC in the joint and confinement regions of the beam and column increased the amount of accumulated energy. On the other hand, at the end of tests, the amount of the total energy was separately obtained as the sum of the amount of the accumulated energy calculated at each cycle for each specimen. The total energy for each specimen is shown in Figure 8 from which he following conclusions can be drawn.

a. The total energy amounts in the beam-column joint specimens subjected to reversed cyclic loads can be increased by using SFRC in the critical regions of beam-column joints.

b. When the behavior of the first and second specimens made of plain concrete is compared, the importance of the column stirrups in the beam-column joint can be seen clearly, i.e. It yielded better ductile beam-column joint behavior.

c. When the results obtained for Specimen # 3 were compared with those of Specimen # 4 it was seen that total energy increased by placing even only one stirrup in the beam-column joint.

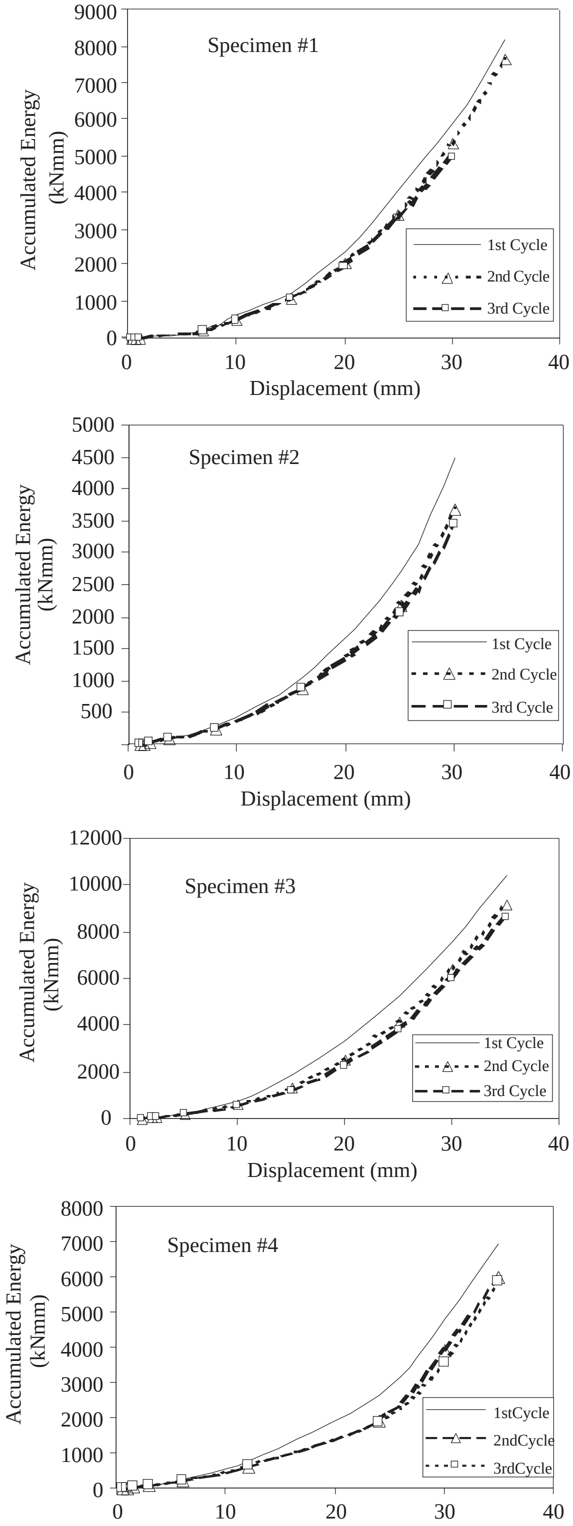


Figure 7. Variation in the accumulated energy as a function of the beam tip displacement of the specimens.

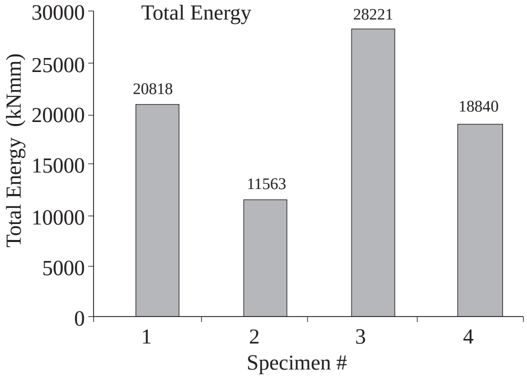


Figure 8. The total energy capacities of the specimens.

The dissipated energy The energy dissipated at the beam-column joint specimens through plastic deformations was the sum of the area in the beam tip force-displacement hysteresis loops as shown in Figure 6. The total amount of dissipated energy of all the specimens are given in Figure 9, which shows that, for Specimens # 3 and # 4 with SFRC, the total amounts of dissipated energy capacities are higher than those of the other specimens. When ductility is defined as the amount of energy absorbed through plastic deformations, the test results showed that the ductility of the beam-column joint could be increased by using SFRC and by decreasing the spacing of stirrups in the joint and confinement regions of the beam and column.

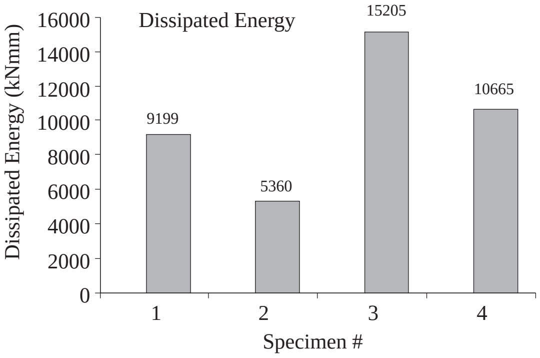


Figure 9. The total amount of dissipated energy.

However, for Specimen # 2 with no transverse reinforcement in the beam-column joint, the amount of energy absorbed was less than those of other specimens. Specimen # 2 displayed more brittle behavior than the other specimens. When plain concrete was used in all regions of the specimen, it was seen that the squeezed column transverse reinforcements in the beam-column joint became of prime importance, when ductile behavior had been required.

The stored energy The amount of energy absorbed through the elastic behavior of the specimens during loading was given back to the system in the course of unloading of the beam-column joint specimens. This energy reserved by elastic behavior was defined as stored energy. The amounts of stored energy of the specimens were separately obtained by subtracting the amount of total dissipated energy from the amount of total energy for each specimen. The stored energy capacities of the specimens are shown in Figure 10.

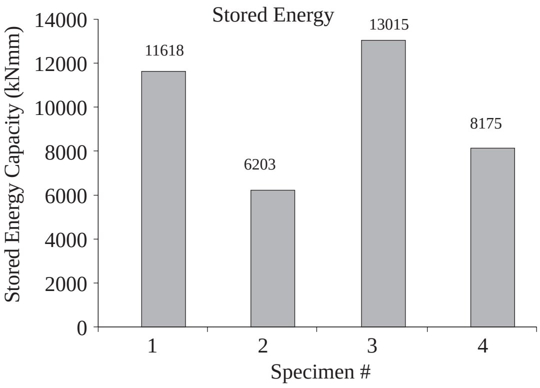


Figure 10. The stored energy capacities of the specimens.

As the figure reveals, the stored energy capacities of Specimens # 1 and # 3 are higher than those of the other specimens, which meants that at the end of the tests, the elastic behavior capability of Specimens # 1 and # 3 was better. Although the spacing of the transverse reinforcements in the joint and confinement regions of the beam and column were decreased, the ductility and strength capacity of the beam-column joint specimens subjected to cyclic loads can be improved by using SFRC in the joint and in confinement regions of the beam and column connections.

Conclusion

Tests on full-scaled exterior beam-column joint assemblies subjected to displacement controlled reversed cyclic loading were carried out. The results indicate that the ductility and strength capacity could be increased by using SFRC and decreasing the stirrups in the joint and confinement regions of the beam and column. Moreover, the use of SFRC and transverse reinforcement in the critical regions can be recommended, in view of the total dissipated and stored energy. Furthermore, the usage of SFRC can reduce the cost of steel reinforcement and its installation, and the difficulties in placing and consolidating the concrete in the regions of the beam-column joints. Thus, SFRC can be seen as an appealing alternative to conventional confining reinforcement. However, it is well known that ductile behavior and the strength capacity of beam-column connections depend on the volume content, aspect ratio of the fibers, fiber type, the regions of SFRC used in joints, the strength of the concrete, and fiber dispersion in the concrete mix. The experimental investigations take account of these parameters on this subject are not still adequate. In a separate study, the authors have planned to investigate the effect of volume content of steel fibers on the rigidity, ductility and deformation energy by considering various parts of the beam and column.

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