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Synergetic effect of steel fibers and shear-reinforcing bars on the shear-resistance mechanisms of RC linear members

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ABSTRACT

Reinforced concrete with steel fibers (RSF) is one type of a hybrid structure that can improve the shear-load capacity of conventional reinforced concrete (RC) structures. This paper studies the synergetic effect of shear-reinforcing bars and steel fibers on the shear-resistance of RSF beams and columns, based on the shape and the distribution of diagonal cracks. A series of bending and lateral cyclic-loading tests were conducted to consider the effect of loading and support conditions on the shear-resistance mechanism. As a result, the optimum ratio of steel fibers to shear-reinforcing bars for the shear-load capacity is determined for the RSF linear members.

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1. Introduction

Reinforced concrete with steel fibers (RSF) could have the higher load-bearing capacity and ductility than conventional reinforced concrete (RC), resulting from the mixing of short steel fibers. It is reported that RSF structures can increase the serviceability and durability of infrastructures [1]. Steel fibers could resist opening and propagation of cracks in concrete, due to the bridging effect of crack surfaces. This implies that steel fibers mixed in concrete might improve the shear-load capacity of reinforced concrete (RC) members, that could result in failure due to the generation of a diagonal crack [2]. Because the standard specifications for concrete structures currently have required large amounts of reinforcing-steel bars to prevent shear failure, it becomes even difficult for RC members to be filled with concrete during construction. One promising method to overcome the problem results in applying short fibers. Many researchers have reported that the addition of steel fibers can significantly increase the shear strength and ductility of RC members. For example, Japanese design guidelines for reinforced concrete piers with steel fiber [1] have regarded steel fibers as the main reinforcement that protects against shear failure in concrete. The prediction proposed for the shear strength of RSF piers in the guideline is based on the fact that steel fibers can carry a larger shear-load than concrete, when steel fibers are mixed into concrete with a volume fraction between 1.0% and 1.5% of concrete volume.

Previous studies considered the effect of steel fibers on the shear-resistance of RC members, based on experimental results of RSF linear members without shear-reinforcing bars [1,3,4] or the plasticity model [5]. The modified truss analogy is applied to consider the shear-load capacity of RC linear members, as a summation of the shear that is carried by the shear-reinforcing bars and the concrete. The shear carried by the steel fibers is usually expressed as a function of the shear carried by the concrete. The standard specifications, however, normally require shear-reinforcing bars in RC members. Since shear-reinforcing bars act as preventing diagonal cracks from crack opening in concrete, reduction of the shear force transferred via crack surfaces by the steel fibers should be effective. Consequently, the combination of both shear-reinforcing bars and fiber reinforcement could expect the synergetic effect for shear-resistance in RSF linear members.

The goal of this study is to clarify the synergetic effect of shear-reinforcing bars and steel fibers on the shear-resistance mechanism of RSF linear members. In order to evaluate the contribution of the steel fibers to the shear-resistance, the ratio of the shear carried by the steel fibers to that of the concrete is studied. A relation between the ratio with the shape of the diagonal crack is in focus, because the shear force that is transferred by the bridging effect of the steel fibers could act as a function of the length and the width of the diagonal crack. A series of bending and lateral cyclic-loading tests are conducted to investigate the synergy effect on the shear-resistance mechanism in RSF linear members. The optimized

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combination of steel fibers and shear-reinforcing bars for the shear-resistance in RSF linear members is clarified.

2. Experimental programs

2.1. RSF beams

2.1.1. Specimen fabrication

Fig. 1 shows an outline of a tested RSF beam. The beam width (b_w) is 150-mm. A shear span (a) is 700-mm and an effective depth (d) is 250-mm. Thus, the shear span to the effective depth ratio (a/d) becomes 2.8. To generate shear failure of diagonal cracks in the specified shear span (right-side in the figure), more stirrups are arranged in the opposite shear span than the tested shear span ($s + s$ in the figure). Specimens are longitudinally reinforced with two deformed PC tendons of 25.4-mm diameter, as the longitudinal reinforcement ratio (p_w) is 2.7%. The yield strength of the PC tendon is 930 N/mm^2, as determined from the 0.2% off-set value. These PC tendons are fixed by anchor plates and bolts to ensure sufficient anchorage. The stirrups are of 6-mm-diameter deformed steel and arranged in the tested shear span as transverse reinforcements with a spacing (s) for a stirrup ratio (r_w) of 0.12–0.30%. The yield strength of rebar was 345 N/mm^2.

Table 1 summarizes mixture proportions of concrete. The compressive strength (f'_c) at the time of the loading test was 51.5–57.5 N/mm^2 for concrete of W/C = 0.335, and 79.9–85.5 for concrete of W/C = 0.30, respectively. The maximum size of coarse aggregate is 20-mm. Mix ratios of admixture (super plasticizer) were adjusted from 0.1% to 1.0% per unit cement weight to obtain good workability and 14-cm slump. Steel fibers were mixed with a volume fraction (SF) of 0.3%, 0.5%, 0.75%, and 1.0% to examine the effect of the steel fiber content on the shear reinforcement. Kodama et al. [3] suggested that RSF beams with SF > 1.0% were difficult to be made and did not have the remarkable reinforcing effect. Table 2 lists material properties of the steel fiber. The steel fiber is of wave shape, 30-mm length with an aspect ratio of 50. The tensile strength is 1.0 kN/mm^2, its specific gravity is 7.85, and the modulus of elasticity is 210 kN/mm^2.

Table 3 summarizes all specimens tested. A total of nine specimens with different SF ratios and stirrup ratios (r_w) were prepared. The specimens are labeled, denoting the SF ratios and stirrup ratios (r_w), e.g., SF03-r18 implies the specimen with 0.3% SF and 0.18% r_w.

2.1.2. Loading method and measurement

Fig. 1 illustrates the details of the loading and supporting positions. The RSF beams were subjected to four-point bending. The specimens were placed over roller supports, which were composed of steel plates with a 100-mm width. Two-point loading with 200-mm interval was applied at the mid-span, where steel plates 100-mm wide, 15-mm thick and 150-mm long were placed. Teflon sheets, of which both faces were greased, were inserted between the RSF beam and the supports to prevent horizontal friction. During the loading test, the applied load, mid-span deflection, strain in the longitudinal reinforcement at the mid-span, and strain in the stirrups at the middle-height were measured by using a load-cell, displacement transducers, and strain gauges.

2.2. RSF columns

2.2.1. Specimen fabrication

Table 1 summarizes mix proportion of concrete employed in the RSF column. The average value of compressive strength f'_c of three samples at the age of 28 days was 37.9 N/mm^2. The steel fibers were mixed with ratios of SF = 0.3% and 1.0%, of which properties were the same as listed in Table 2. Fig. 2 shows a test set-up of the RSF column. The column has the following dimensions: loading height, a = 800-mm and effective depth, d = 210-mm; thus, a/d = 3.81. The column width (b_w) is 150-mm. The column specimens are longitudinally reinforced with four deformed PC tendons of 22.2-mm in diameter, as the longitudinal tensile reinforcement ratio (p_w) is 2.46%. The yield strength of the PC tendon is 1198 N/mm^2 determined from the 0.2% off-set value. These PC tendons are fixed at the footing by plates and bolts to ensure sufficient anchorage. Tie bars of 6-mm-diameter deformed bars are arranged with spacing s a shear-reinforcing bar ratio (r_w) of 0.0%, 0.21%, and 0.42%. The yield strength of the tie bars (f_{wy}) is 345 N/mm^2. Table 3

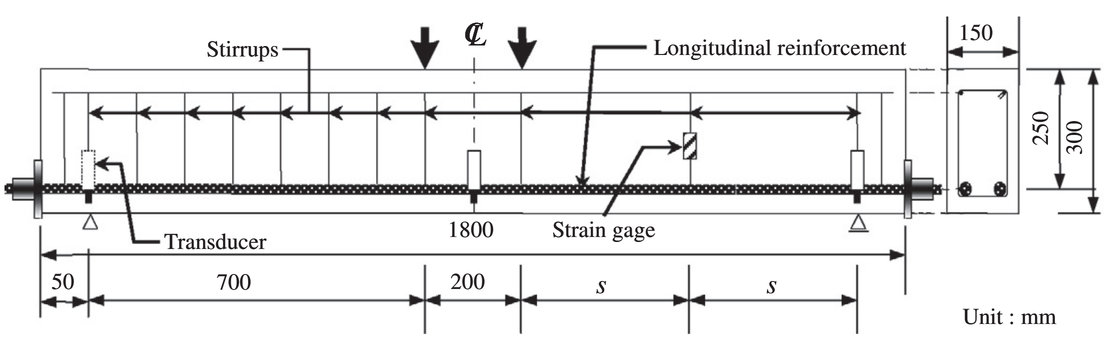

Fig. 1. Sketch of a tested RSF beam.

Table 1
Mixture proportions of concrete.

Type	G_{max} (mm)	Slump (cm)	W/C	Air content (%)	s/a (%)	Unit weight (kg/m^3)				Super plasticizer[a] (%)	SF[b] (%)
						Water	Cement	Sand	Gravel		
Beam	20	14	0.30	4.5	51.2	165	550	847	790	0.1–1.0	0.3, 0.5, 0.75, 1.0
			0.335		53.1	165	471	917	790		
Column			0.55		47.0	172	314	838	950		0.3, 1.0

[a] Percentage to cement weight.
[b] Volume fraction of steel fibers to full concrete volume.

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