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Shear Behavior of Reinforced Concrete Beams with Hybrid Crimped-Hooked End Steel Fibers-Modified Polypropylene Fibers

S. Maghsoodian[1], F. Jandaghi Alaee[1], M. Nematzadeh[2]

[1] Shahrood University of Technology
[2] University of Mazandaran, Babolsar, Iran

ABSTRACT: One undesirable failure mode in reinforced concrete beams is the shear failure mode without prior warning before the flexural failure. Supplying minimum shear reinforcement (stirrups) is one of the ways to avoid such failure at low levels of shear loads. Due to construction difficulties in places with reinforcement congestion, an alternative to minimum stirrups is to use fibers. This study focused on the effect of the combination of crimped-hooked end steel fibers and modified polypropylene (PP) fibers on the shear behavior of reinforced normal strength concrete beams. The obtained results were compared with the shear behavior of the section reinforced with minimum shear reinforcement under the same conditions, and the feasibility of using the above hybrid fibers as a replacement for the minimum shear reinforcement was evaluated based on the guidelines of ASTM C1609 and the acceptance criteria of the ACI 318-2011.

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1- Introduction

The application of plain concretes is widespread due to their low cost and the availability of their constituent materials. However, some defects such as low tensile strength and strain capacity are observed in such concretes, which lead to their weakness against crack opening and propagation [1-4]. Using steel and polypropylene (PP) fibers in their hybrid form enhances the characteristics of fresh concrete, such as reduced initial cracks for the freshly casted concrete, and those of hardened concrete, such as compressive strength, ductility, and toughness with low cost [5-7]. The model presented by ACI 318-2011 [8] for calculating the shear strength of plain (fiberless) concrete beams without shear reinforcement is in the form of $V_c = 0.167\sqrt{f'_c}\, b.d$, where f'_c is the concrete compressive strength, b is the cross-sectional width, d is the cross-sectional effective height, and V_c is the resisting shear force in the SI system developed based on the empirical results obtained for specimens with effective height ranging from 254 to 375 mm. However, according to the results reported by other researchers, this formula is not acceptable for sections with greater heights. Given the above discussion, to avoid the brittle shear failure and the uncertainty of the formula proposed for calculating the shear capacity, the ACI 318-2011 [8] requires the design of minimum shear reinforcement for lengths of the beam in which $\frac{\varphi V_c}{2} < V_u < \varphi V_c$, and steel fibers can replace the minimum stirrups complying the ASTM C1609 standard [9].

*Corresponding author's email: m.nematzadeh@umz.ac.ir

2- Experimental program

2- 1- Materials and mixture proportions

Here, Portland cement Type II supplied from Faraz Firouzkouh Cement Company, Mazandaran, Iran, was used. Furthermore, the used fine stone aggregate had a fineness modulus of 2.8, a specific gravity of 2.61, water absorption of 1.7%, and a maximum particle size of 4.75 mm. In addition, the used coarse stone aggregate had a specific gravity of 2.67 and a maximum particle size of 12.5 mm. The fibers were produced by Erfan Maftool Co., Iran, and both crimped and hooked end types were incorporated in a single sample of steel fibers to be able to employ the maximum capacities of the fibers. In addition, to prevent the appearance of micro-cracks at the initial stages of loading as well as those due to moisture changes and temperature changes modified PP fibers were used in a hybrid form together with the steel fibers.

2- 2- Test setup of reinforced concrete beams

The beam specimens were constructed on a 1/2 scale and tested under the four-point bending where the concentrated load was applied at points located at 1/3 of the support span via an I-shaped composite steel beam.

2- 3- Details of reinforced concrete beams

Details of the reinforced concrete beams tested here are provided in Table 1. Here, 16 reinforced concrete beams with a width of 220 mm, a height of 300 mm, and a length of 2270 mm was constructed and exposed to flexural loading until

Table 1. Details of concrete beams

Beam group	Specimen ID	Longitudinal reinforcement ratio	Fiber volume fraction	Shear reinforcement
A	A_{1-1}	2.5	-	
	A_{1-2}	2.5	-	
	A_{2-1}	4	-	
	A_{2-2}	4	-	
B	B_{1-1}	2.5	-	minimum
	B_{1-2}	2.5	-	minimum
	B_{2-1}	4	-	minimum
	B_{2-2}	4	-	minimum
C	C_{1-1}	2.5	0.75% steel+ 0.25% polymeric	
	C_{1-2}	2.5	0.75% steel+ 0.25% polymeric	
	C_{2-1}	4	0.75% steel+ 0.25% polymeric	
	C_{2-2}	4	0.75% steel+ 0.25% polymeric	
	C_{3-1}	2.5	1% steel+ 0.25% polymeric	
	C_{3-2}	2.5	1% steel+ 0.25% polymeric	
	C_{4-1}	4	1% steel+ 0.25% polymeric	
	C_{4-2}	4	1% steel+ 0.25% polymeric	

Group A: beams without shear reinforcement and fibers, Group B: beams with minimum shear reinforcement, and Group C: beams with fibers

failure. In the tests on the beams, the effect of the fiber volume ratio and longitudinal reinforcement ratio were investigated. Furthermore, the behavior and shear capacity of the beams, as well as crack development in them, were explored in different cases including the section with plain concrete, the one with fiber-reinforced concrete, and the one with minimum shear reinforcement.

3- Experimental results

Tests for the compressive strength and flexural strength of the concrete specimens were carried out after 28 days of curing by the ASTM C39 and ASTM C1609. In this regard, the hybrid form of the steel-PP fibers was accepted as the minimum shear reinforcement by ACI318-2011 [8].

It was observed that regardless of the effect of the presence of steel and PP fibers or stirrups, all of the beams experienced shear failure in the form of a severe reduction in the load-carrying capacity of the beam without significant change in the mid-span deflection. Although the presence of the steel fibers led to the formation of further cracks and opening of cracks in the section, in most cases, failure was sudden and accompanied by a loud sound. Table 2 gives the general properties of the failure mode of the beams.

In the present study, based on the failure results of the beams and the evaluation of all the cracks at the mid-height of the beams with angles ranging from 0-75 degrees from the longitudinal direction of the beam, the crack spacing was obtained as 9-15 mm for the beams with plain concrete and shear reinforcement, 5-11 mm for the beams with 0.75% steel fibers, and 4-7 mm for the beams reinforced with 1% steel fibers.

4- Proposed model for shear strength

In the end, based on the experimental findings of this research and via investigating the sensitive parameters in formulas proposed by other researchers, Eq. 1 was presented for calculating the shear strength of concrete reinforced with fibers. This formula demonstrated good accuracy ($R^2 = 0.98$).

$$V_u = (0.167 + 0.664 V_f \frac{l_f}{d_f}) \sqrt{f_c'} + 13.17 (\rho \frac{d}{a})^{0.857} \quad (1)$$

5- Conclusions

A summary of the results is provided below.

1. By adding crimped-hooked end steel fibers at volume ratios of 1 and 0.75% and polypropylene (PP) fibers at a volume ratio of 0.25, the ductility of the section increased, and also, numerous cracks nearby were observed in the beam specimens.

2. By adding crimped-hooked end steel fibers at 0.75% and PP fibers at 0.25% of the concrete volume, the concrete shear strength of greater than $0.33\sqrt{f_c'}$ was observed in the tested specimens.

3. As the volume ratio of the fibers increased, the angle between the critical crack and the horizontal axis decreased, and the effect of a change in the longitudinal reinforcement ratio on the angle of the critical crack and ultimate shear force was not significant compared with the effect of a change in the fiber volume ratio.

4. By adding at least 0.75% steel fibers with 0.25% PP fibers in the concrete mixture and conducting the tests by ASTM C1609, together with investigating the acceptance criteria of hybrid fibers as the minimum shear reinforcement by the ACI 318-2011, the above fibers were accepted.

Table 2. General properties of the failure mode of the beams

Specimen ID	Concrete compressive strength $f'_c(N/mm^2)$	Failure load (kN)	$\frac{V_{test}}{b.d\sqrt{f'_c}}$ $(N/mm^2)^{0.5}$	Crack space (mm)	Critical crack distance from the support (mm)	Critical crack angle (Degree)	Crack angle in the middle of beam height (Degree)	Maximum deflection (mm)
A_{1-1}	35.9	127	0.185	11-15	Right support-350	27	Flexure, 45	6.2
A_{2-1}	38.7	179	0.251	11-16	Left support-330	35	Flexure, 50	17.1
B_{1-2}	37.0	222	0.318	11-15	Right support-330	30	Flexure- Shear, 45	23
B_{2-2}	33.2	230	0.348	9-14	Left support-400	30	Flexure- Shear, 45	31.6
C_{1-2}	37.7	381	0.54	7-11	Left support-400	32	Flexure- Shear, 45	31.5
C_{2-2}	36.9	396	0.561	5.5-8	Left support-380	30	Flexure- Shear, 35	30.8
C_{3-2}	40.7	473	0.59	5-6	Left support-400	30	Flexure- Shear, 30	32.54
C_{4-2}	37.2	430	0.61	4-7	Right support-330	28	Flexure- Shear, 25	33

5. Using the experimental results of this study and by investigating the sensitive parameters in formulas proposed by other researchers, a formula was presented to calculate the shear strength of fiber-reinforced concrete, which demonstrated a proper accurac

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