Construction and Building Materials 83 (2015) 150–158

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of steel and synthetic fibers on shear strength of RC beams without shear stirrups

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HIGHLIGHTS

- Polypropylene fiber reinforced concrete beams exhibited reduced shear strength.
- Combined fiber reinforced concrete beams exhibited multiple shear cracks.
- A minimum of 0.5% of steel and polypropylene fibers can replace the stirrups.
- Both steel and polypropylene fibers of 1% can improve the shear strength.

ARTICLE INFO

Article history:
Received 16 November 2014
Received in revised form 24 February 2015
Accepted 4 March 2015

Keywords:
Failure mechanism
Fiber reinforced concrete
Mechanical testing
Polypropylene fibers
Shear strength
Steel fibers

ABSTRACT

This study presents the influence of the type and volume fraction of fibers in the concrete mix on the shear strength of RC beams. One RC (control) and six fiber reinforced concrete (FRC) beam specimens are tested under the gradually increasing monotonic loading. Both high-modulus (steel) and low-modulus (polypropylene) fibers of either 0.5% and 1% volume fraction in concrete are used in FRC specimens. Shear stirrups are completely eliminated in the half-span of the FRC specimens. A better post-peak residual strength response is noticed in case of all FRC beam specimens due to multiple cracking associated with the fiber bridging action. The main parameters investigated are shear strength, failure mechanism and displacement ductility. In the absence of shear stirrups, the peak shear resistance and mid-span displacement of the FRC specimen 1% of polypropylene fibers only reached about 70% and 50% of corresponding values for the RC specimen. The FRC specimens with combined steel and polypropylene fibers of minimum volume fraction of 0.5% in the concrete reached the same shear strength as RC specimen in the absence of shear stirrups. However, the shear resistance and deformability values are improved by 20% and 40%, respectively, when the polypropylene fibers of 1% of volume fraction were added to the concrete in addition to the steel fiber of 1% fiber content. Further, multiple cracks of smaller crack width are noticed at the failure stage of the CFRC specimens indicating the better fiber bridging action of combined metallic and nonmetallic fibers.

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1. Introduction

Fiber reinforced concrete (FRC) has been widely used in industrial pavements and non-structural elements, such as, pipes, culverts, tunnels, and precast elements [1–3]. The addition of randomly oriented discontinuous fibers in cementitous materials reduces the level of micro-cracking and enhances the toughness, ductility and post-cracking tensile resistance of concrete members [4–6]. The strengthening effect of fibers in the concrete matrix is achieved primarily due to the bridging effect of fibers at the crack interfaces. The primary failure mechanisms of fibers in the concrete matrix are fiber pullout, fiber rupture, and fiber debonding [7]. The properties of fibers play an important role in determining the predominant mechanism of failure as well as on the macroscopic behavior of the cracked FRC members [8,9]. While the small-sized (micro) steel fibers in the concrete mix enhances the compressive and splitting tensile strengths, the large-sized (macro) fibers, on the other hand, yield the opposite mechanical effects [10–12]. Different fibers used in the structural concrete applications can be broadly divided into two categories, namely, high-modulus (metallic) and low-modulus (non-metallic). Steel and polypropylene are extensively used as the metallic and non-metallic fibers in the FRC applications, respectively [13]. Polypropylene fibers in the concrete mix provide the advantages of higher durability [14], reducing the shrinkage of concrete [15–

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http://dx.doi.org/10.1016/j.conbuildmat.2015.03.010
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17], and reducing the spalling effect in high-strength concrete subjected to elevated temperatures [18]. These fibers are particularly effective in controlling the propagation of micro cracks in concrete because of the lower stiffness, high aspect ratios, and increased number of fibers at a given volume fraction.

Usually, plain concrete fails in a brittle manner at the occurrence of cracking. The addition of steel fibers help the concrete to carry stresses well beyond the cracking, thus maintaining the structural integrity. The effectiveness of steel fiber reinforced concrete (SFRC) in improving various mechanical properties of concrete largely depends on the fiber dosage, fiber aspect ratio, amount of longitudinal steel, tensile strength of fibers, and concrete compressive strength. It has been recognized that the strength and ductility of concrete is partially improved by addition of only single type (steel or polypropylene) of fiber. Combining different types of fibers to optimize the mechanical performance of concrete has been acknowledged [6], which resulted in combined (hybrid) fiber reinforced concrete (CFRC). The effect of quantity of each type of fiber on the mechanical properties of CFRC has been studied previously [11,13]. However, limited studies have been carried out to study the behavior of RC beams with combined fibers in the concrete mix in the presence of conventional longitudinal and transverse reinforcements.

Therefore, for the purpose of exploring the load resisting capacity and failure behavior of RC beams with the inclusion of combined fibers in concrete mix, an experimental program have been conducted in this study. Seven full-scale beam specimens are tested under monotonically increasing loading for the various combinations of both steel and polypropylene fibers of varied volume fractions. The conventional transverse stirrups in the RC beam have been completely eliminated in the fiber reinforced concrete regions of FRC specimens. The main objectives of this study are (i) to investigate the shear strength, failure mechanism, and ductility of FRC beams with combined fibers; (ii) to evaluate the mechanical properties of FRC with both steel and polypropylene fibers; and (iii) to find out whether there is an optimum fiber content for CFRC in order to replace the shear stirrups in the RC beams. The goal is to improve the lateral strength and ductility of RC beams by combining the fiber bridging characteristics in the concrete with minimum requirements of transverse stirrups.

2. Review of past research

Past studies [11,13,19–21] have shown that the tensile and compressive strengths, flexural properties, toughness, and fracture behavior of concrete can be also improved by adding polypropylene fibers into the concrete mix. While the compressive strength of concrete is less affected by the addition of steel fibers, the splitting tensile strength of concrete can be enhanced by 10–50% depending on the fiber aspect ratio and volume fraction [22]. In addition, the ultimate and residual flexural strengths, ductility, flexural toughness, and fracture properties of concrete members can be enhanced due to the addition of steel fibers in the concrete mix [23–30]. In the recent years, there has been a growing interest in the construction industry to use the fiber reinforcement to reduce the complexity in the reinforcement detailing in the RC members. Extensive studies (e.g., [31–34]) have concluded that the shear strength and ductility of RC members can be significantly enhanced by using adequate amount of steel fibers in the concrete matrix. In addition, FRC helped in changing the failure mechanism from brittle to ductile due to stress redistribution and multiple cracking phenomena. The contribution of steel fibers in enhancing the shear strength of RC members has been recognized in ACI 318-08 [35] that recommends the use of a minimum volume fraction of 0.75% ($\sim$60 kg/m^3) of deformed steel fibers as a partial replacement to the shear stirrups in RC flexural members.

Steel fibers of high volume fraction in the concrete mix have potential disadvantages in terms of the poor workability and the increased cost. Further, the stiffer steel fibers may result in voids and honeycombs in concrete during placing because of improper consolidation at low workability levels. By using both metallic and non-metallic fibers in the concrete mix, the properties of fresh concrete such as, better workability and reduced early-age cracking and of hardened concrete such as, better strength, ductility and toughness can be improved at a reduced overall cost [6,13]. Both low and high modulus fibers help in arresting the micro- and macro-cracks in concrete, respectively. The addition of both steel and polypropylene fibers to the concrete improved the tensile strength [36], flexural strength and toughness [9,37–39] of concrete members while reducing the crack propagation as compared to those with the addition of single type of fiber. A significant post-yield strain-hardening response of FRC members can be expected if both steel and polypropylene fibers are added in an equal volume fraction of 1% to the concrete mix [40]. However, the improvement of shear behavior of FRC members with both metallic and non-metallic fibers has not been explored in detail. Hence, there is a need of further study on the investigation of fiber content of both types of fibers on the shear strength of large-scale RC flexural members.

3. Research significance

In case of the conventional RC members, brittle shear failure is usually avoided by providing transverse stirrups along their lengths. The requirement of closely-spaced stirrups in the critical regions of the RC members, many times, creates congestion making the placement of concrete more difficult. Further, the preparation of these stirrups requires extensive labor-intensive work. Though the use of SFRC have shown to provide the required shear strength of RC members, steel fibers may be expensive particularly when there is a requirement for higher fiber content in the concrete. Past studies have shown that the less-expensive polypropylene fibers can be added along with steel fibers in the concrete mix to improve the compressive, splitting tensile and flexural strengths as well as ductility of concrete. However, it is important to study the effect of relative fiber doses of both these types of fibers in the concrete mix to get the desired performance of RC flexural members. The present study provides an insight on fiber doses of both steel and polypropylene fibers in the concrete mix that can replace the conventional transverse shear stirrups in order to achieve the improved lateral load-resisting capacity as well as the desired failure mechanism of the RC members.

4. Experimental program

An experimental investigation has been conducted on seven full-scale test specimens prepared using plain and fiber reinforced concrete. Two types of fibers, namely steel and polypropylene, with fiber volume fraction of 0.5% or 1.0% were used in the test specimens. Three-point bending tests were conducted on the full-scale beam specimens. In addition, standard tests were carried out on concrete cubes, cylinders, and small-scale beams to investigate the role of fiber type and fiber content on the compressive, splitting tensile and flexural strengths of concrete. The details of test specimens, mix design, materials, instrumentations, and test set-up used in this study are discussed in the following sections.

4.1. Test specimens and reinforcement detailing

All test specimens used in this study were 2.0 m long with an effective span of 1.8 m. The width and overall depth of specimens

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