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Shear behavior of basalt fiber reinforced polymer (FRP) and hybrid FRP rods as shear resistance members

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HIGHLIGHTS

- The shear stress to deformation relationship model of BFRP rods.
- Parameters affecting shear property of BFRP rods.
- Prediction of shear strength of BFRP rods.

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ABSTRACT

This paper investigates the shear properties of basalt fiber reinforced polymer (BFRP) and the hybrid FRP rods as shear resistance members. The shear properties of FRP rods and the corresponding resin casting rods were studied separately, including variables representing rod diameters of 4–16 mm, resin types of epoxy and vinyl ester resins and fiber types comprising basalt, carbon and their hybridization. The ratio between shear stress and shear deformation was first described according to experimental results, and the shear contribution mechanism was clarified for different stages. An equation for predicting the shear strength of BFRP and hybrid FRP rods was proposed by discussing the influence of different variables. The results show that the shear strength and shear deformation ratio of different FRP rods is maintained almost constantly regardless of the variation in diameters, resin types and fiber types. The major shear resistance in FRP rods is contributed by the internal fibers, whereas the resin contributes only 8% of the overall strength and acts only in the first stage. A three-stage model is proposed to describe the entire stress to deformation ratio. A derived equation based on the shear contribution analysis is also used to predict the shear strength of the BFRP and hybrid FRP rods with high accuracy.

1. Introduction

Fiber reinforced polymer (FRP) composites are widely accepted as structural reinforcing materials in the civil, environmental, energy and aerospace engineering fields owing to their superior physical, mechanical and chemical properties compared to conventional steel reinforcement [1,2]. A typical civil engineering application for FRP involves applying it as an internal or external structural rod reinforcement, such as FRP bars or cable and anchor bolts that replace conventional steel rods in reinforced concrete (RC) structures and cable-supported bridges [3–6]. Although the tensile behavior of FRP is a major concern when determining structural behavior such as strength and stiffness in typical rod applications, the shear behavior should also be evaluated to guarantee tensile behavior with maximum performance. For instance, FRP bars as stirrups in RC members also suffer from shear force due to dowel action induced by concrete cracking in addition to tensile action that transfers shear force. FRP anchor bolts or connection bolts carry shear force directly to transfer structural loads. Thus, the shear properties of these FRP rods should be clarified and evaluated to make sure a structure's overall behavior can perform up to standards.

Basalt FRP (BFRP) is a newly developed composite material that is comparable to carbon FRP (CFRP), aramid FRP (AFRP) and E-glass FRP (GFRP) composites and has received wide attention in strengthening construction [7]. Basalt fibers are environmentally friendly, inorganic materials produced from volcanic rock using a single raw material and drawing fibers from molten rock at a

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temperature of 1400–1500 °C. The most attractive characteristic of BFRP is its integrated properties that are superior to conventional FRP composites, including its >20% higher strength and modulus, comparable cost, and greater chemical stability compared to GFRP, a wider range of working temperatures and a significantly lower cost than CFRP [8,9]. Although BFRP exhibits superior or competitive properties compared to conventional materials, it suffers from limited applications due to a lack of sufficient, comprehensive understanding of its mechanical and chemical properties in terms of both shear and time. The shear behavior of BFRP has not yet been investigated in the literature. Therefore, a comprehensive understanding of BFRP's shear behavior and the prediction of its shear strength is necessary for its safe and reliable application as a structural shear resistant member in engineering applications.

2. Literature review

Previous studies on the shear behavior of FRP composites have focused mainly on the in-plane and interlaminar shear behavior of laminated composites, for which interlaminar behavior is regarded as a critical weak point in their overall performance [10]. The interlaminar shear behavior exhibits a completely different failure mechanism from the shear behavior of the FRP rod's transversal direction because the shear behavior of interlaminar composites is controlled by the resin's shear properties and the interfacial behavior of the fibers' laminate and resin, whereas the shear behavior of the FRP rod's transversal direction is determined by the interaction between the fibers and resin [11]. The analysis yielding behavior the most similar to the shear behavior of the FRP rod's transversal direction has been identified for the specific members of connection joints such as bolts, which are usually composed of carbon fibers and epoxy resin [12]. A relevant analysis of a bolted joint has focused mainly on the load transfer elements instead of the composite bolt itself and the effect of the clearance between the bolt and hole [13]. However, during the application of FRP rods for structural strengthening, such as concrete reinforcement and the cables in suspension bridges, the shear behavior of the FRP rod itself determines the overall structural behavior. Moreover, and differing from the composition of other types of composites, FRP rods are usually made by the pultrusion of one-directional fibers with various kinds of matrices such as epoxy, vinyl ester and unsaturated resins. The hybridization of different kinds of fibers is often adopted for FRP rods to increase their elastic modulus and modify the stress–strain relationship according to the structural requirements for stiffness and ductility [14]. Thus, any investigation of an FRP rod's shear behavior, especially newly developed BFRP rods and the relevant hybrid FRP rods, should emphasize the characteristics that directly affect structural performance when these FRP rods are used for strengthening.

Therefore, this paper investigated the individual parameters potentially affecting the shear behavior of FRP rods, including fiber types, matrix types and rod diameters, while the shear behavior of different types of FRP rods were modeled and the corresponding strengths were predicted based on the shear failure modes and shear contribution from different components of the FRP rods.

3. Experimental program

The test method for determining the shear properties of FRP rods was created according to the transverse shear test method in ACI 440.3R-04 [15], which is more widely adopted as a method for determining material shear strength and guiding structural design than other shear test methods such as the short-beam test [16]. The most important requirement is that the load direction and boundary condition be similar to the action in real applications such as the use of FRP rods in concrete and as suspended cables. Thus, the results from this test method can be used directly to guide such applications.

3.1. Parameters and specimen preparation

Considering the typical application of BFRP rods in construction engineering, six rod diameters ranging from 6 mm to 16 mm were selected to investigate the effect of size on shear behavior. BFRP rods with two kinds of matrices, epoxy and vinyl ester resins, which are both commonly used for FRP rods, were adopted to verify the influence induced by the compatibility of basalt fibers and these resins. CFRP rods and hybrid basalt and carbon FRP rods with three hybridization proportions, potentially used as cables for long-span bridges [17], were also adopted to investigate their shear behavior and the hybrid effect in shear. In addition, to clarify the shear strength contribution of FRP rods, corresponding resin casting rods with diameters of 6 mm, 8 mm and 10 mm diameter were prepared. Two types of hardening temperatures were adopted for the resin casting to investigate their differences. The details of the experimental parameters are listed in Table 1.

All of the FRP rods were produced by the pultrusion method. The basalt fiber roving, of the type 2400tex and with a single fiber diameter of 13 μm, was provided by Jiangsu GMV New Material T&D Co., Ltd., China [18], and the carbon fiber roving, with 12 k and of the type T300, was provided by Toray, Japan [19]. The vinyl ester and epoxy resin were provided by the Wuxi and Shanghai resin companies of China, respectively. All of the FRP rod specimens were cut to a length of 300 mm to fit the shear test equipment according to ACI 440.3R-04. The resin casting rods were produced in a polyethylene (PE) mold with a hollow tube. The release agent was used to assure the separation of the resin casting rods from the mold after hardening. Each of the ten specimens was prepared for each type of rod, and at least five valid specimens were used to determine the shear properties. The prepared FRP rod and resin casting rod specimens are shown in Fig. 1.

3.2. Test setup and loading procedure

The shear tests for the FRP rods, including the BFRP, CFRP, hybrid B/CFRP and resin casting rods, were conducted on a MTS-SANS tension–compression test machine with a capacity of 500 kN. The specimens were first installed in a double

Table 1
Experimental specimen information.

Type		Fibers	Matrix	Nominal diameter (mm)	Tensile elongation[20] (%)
BFRP rods	BV-4	Basalt fibers	Vinyl ester resin	4	3.14
	BV-6			6	
	BV-8			8	
	BV-10			10	
	BV-12			12	
	BV-16			16	
	BE-6	Basalt fibers	Epoxy resin	6	3.20
CFRP rods	CV-6	Carbon fibers	Vinyl ester resin	6	1.23
Hybrid FRP rods	B1C1V-6	Basalt/carbon (1:1)	Vinyl ester resin	6	1.45
	B3C1V-6	Basalt/carbon (3:1)		6	1.50
	B4C1V-6	Basalt/carbon (4:1)		6	1.48
Resin casting	RH-6	–	Vinyl ester resin (high temperature curing, 150 C)	6	3.1
	RH-8	–		8	
	RH-10	–		10	
	RL-6	–	Vinyl ester resin (room temperature curing)	6	3.3
	RL-8	–		8	
	RL-10	–		10	