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Investigating the flexural resistance of fiber reinforced cementitious composites under biaxial condition

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ABSTRACT

The flexural resistance of fiber reinforced cementitious composites (FRCCs) under biaxial condition was investigated by using two different types of biaxial bending test methods: the biaxial flexural test (BFT) and the centrally loaded round panel test (RPT). The flexural responses of FRCCs under biaxial condition were then compared with those of FRCCs under uniaxial condition; i.e. four-points bending test (4PBT). The test results, including the equivalent biaxial strength and normalized energy absorption capacity of the RPT, were found to be clearly higher than those of the BFT, and completely different cracking behavior was observed between the two biaxial test methods; the BFT generated numerous randomly distributed micro-cracks at the bottom of specimens, whereas the RPT mostly showed three major cracks, with minor radial cracks around them. In addition, the equivalent flexural tensile strength and normalized energy absorption capacity of the FRCCs under biaxial condition were found to be higher than those under uniaxial condition. The energy absorption capacity and the ratio of flexural tensile strength to the direct tensile strength of FRCCs are dependent on the stress state.

1. Introduction

Fiber reinforced concrete (FRC) and fiber reinforced cementitious composites (FRCCs) are widely used in civil infrastructures including airports, highways, industrial floors, bridge decks, elevated slabs, overlays, tunnel linings, and precast elements [1–5], owing to their much high load carrying capacity and crack resistance. In the application of FRCCs, it is very important to control the quality or performance of FRCCs, in both precast and cast in situ FRCC products. The most popular test method for the quality control of FRCCs is the three- or four-point bending test (4PBT) [6–11] under uniaxial loading condition, because the composite components tend to be loaded in uniaxial bending rather than in axial tension, and the 4PBT offers simplicity of testing. The bending test method using beam specimens provides the flexural strength and energy absorption capacity (or toughness) of FRCCs under uniaxial flexural condition (e.g., the beam or girder). However, most infrastructures such as elevated slabs, floors, bridge decks, and capping layers of high speed rails (HSRs) structures [12] are primarily under biaxial flexural load condition. Thus, for the design of these structures using FRCCs by considering their actual performance, the flexural resistance measured from the uniaxial flexural stress test results needs to be justified for biaxial stress states; it is thus necessary to investigate the flexural behavior of FRCCs under biaxial tensile loading condition.

In estimating their biaxial flexural behavior, two test methods are currently available.

One is the centrally loaded round panel test (RPT, ASTM C 1550, see Fig. 1(a)) [13], which determines the flexural toughness, an energy absorption capacity in the post-crack range of FRCs using a round panel [14–19]. Bernard [14,15] reported that the assessment of panel-based performance is more desirable for an in situ fiber reinforced shotcrete (FRS) lining. They also mentioned that the results from RPT showed higher precision in estimating the post cracking behavior of FRS. Rambo et al. [19] investigated the mechanical behavior of hybrid steel-fiber self-consolidating concrete under bi-axial bending, which was addressed using the RPT. They demonstrated that the RPT allowed the formation of a multiple cracking pattern which was not observed in the four point beam tests. On the other hand, Kim et al. [20] reported that the results from the RPT might not represent the biaxial resistance of FRCCs, owing to the triple axisymmetric stress distribution of the RPT, causing the specimen to break into three pieces upon failure.

The other test method is the biaxial flexure test (BFT), illustrated in Fig. 1(b). The BFT was originally developed by Zi et al.

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[21] to determine the biaxial flexural strength of plain concrete. The BFT using a circular plate is a simple axi-symmetric form of 4PBT. The BFT successfully generated constant biaxial moment within the inner loading ring of a specimen, similar to the constant uniaxial moment zone of the 4PBT [12,20]. Thus, BFT could consider the statistical nature of the material properties [22]. Using the BFT, the biaxial flexural properties of concrete have been intensively investigated by Zi et al. [23], Kim et al. [24,25], and Kirane et al. [26].

The aim of this study is to investigate the flexural performance of fiber reinforced cementitious composites (FRCCs) under biaxial condition. The objectives are (1) to obtain the equi-biaxial flexural stress versus normalized deflection responses of FRCCs under biaxial condition, (2) to compare the biaxial flexural behavior of FRCCs, according to the two different test methods, and (3) to investigate the correlation between the uniaxial and biaxial flexural resistance of FRCCs.

2. Biaxial behavior of concrete and FRCCs

Much research has been performed on the behavior of plain concrete under biaxial stress states, including compression to compression, compression to tension, and tension to tension [27–32]. Kupfer et al. [27] and Nelissen [28] reported that the strength of concrete under biaxial tension is similar to the uniaxial tensile strength, whereas Tasuji et al. [29] reported that the biaxial tensile strength of concrete is higher than the uniaxial tensile strength.

The behavior of FRC or FRCCs under biaxial stress state (compression to compression, or tension to compression) has been investigated by several researchers [33–38]. Yin et al. [33], Traina and Mansour [34], and Sirijaroonchai et al. [38] investigated the behavior (ultimate strength, stress–strain relationships, and failure mode) of FRC or high performance fiber reinforced cement composites (HPFRCCs) under biaxial compressive loading. They found that the ultimate strength of the fiber concrete in biaxial compression was greater than in uniaxial compression, due to the increased confinement from biaxial compression; and there are significant differences in the stress–strain relationships and failure modes of FRC under uniaxial and biaxial compressive loading. To perform biaxial tests for plain concrete and FRCCs, they carried out tests using a square plate or cube specimen, and estimated the behavior of FRCCs subjected to biaxial loading in a compression to compression stress state. To produce biaxial stress, sophisticated test set-ups were required, sometimes with multiple actuators; they should then be installed correctly because the fracture tends to be localized in a specific direction and its field applicability is therefore low.

Until now, however, no data has been reported on the biaxial tensile behavior of FRCCs, although FRCCs are commonly used in construction applications subjected to biaxial tensile loading. This is mainly because of the difficulties associated with tension–tension testing of composite materials. The direct tensile test method is rarely used, due to the difficulties associated with the gripping and alignment of a specimen when measuring the tensile strength of plain concrete. In contrast, the indirect method as a three- or four-point bending test is most popular in practice because of its simplicity. In this study, therefore, the indirect biaxial test methods, the RPT and the BFT, instead of the direct biaxial tension test, were used for estimating the biaxial tensile behavior of FRCCs.

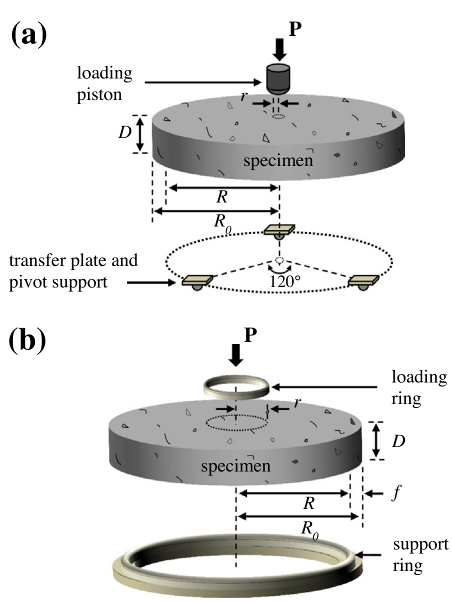

Fig. 1. Schematic view of (a) RPT and (b) BFT methods.

3. Uniaxial and biaxial flexural parameters of FRCCs

Fig. 2 shows the typical flexural tensile behavior of FRCCs. According to the ASTM standard for the evaluation of flexural performance of FRC or FRCCs, the fracture toughness of FRCCs may be defined as the area under the load–deflection curve up to a certain deflection rather than the area under the complete load–deflection curve with a maximum deflection corresponding to the load reduced to zero. In the case of the uniaxial flexure bending test, ASTM C 1609 recommends four different deflections for the evaluation of the toughness: the deflection corresponding to first-peak and peak loads, 1/600, and 1/150 of the span length. The toughness measure of a round panel specimen is given in ASTM C 1550. Similar to the uniaxial case, the toughness is also defined as the area under the load–deflection curve. The standard recommends four different deflections of 5, 10, 20, or 40 mm at the center of specimens to evaluate the toughness.

Before a first crack is initiated, the contribution of fibers to the load resistance mechanism of FRCCs is marginal. Therefore, the toughness value calculated by using the deflection at the first crack represents the toughness of the concrete. After the first crack formed and before the overall load–deflection curves soften, many small cracks develop. In this region, fibers bridge between the surfaces of these cracks. Here, fibers contribute significantly to the toughness of composites. Beyond the peak, the cracks are localized to a few macro cracks.

In this study, to examine the effect of different stress states or test methods on the behavior of FRCCs after the first cracking, the toughness of FRCCs is evaluated by using the deflections at two points in the equivalent flexural tensile stress (f_t) versus normalized deflection from a span length (δ/L) curve as shown in Fig. 2. The first point is the limit of the linear elasticity at which

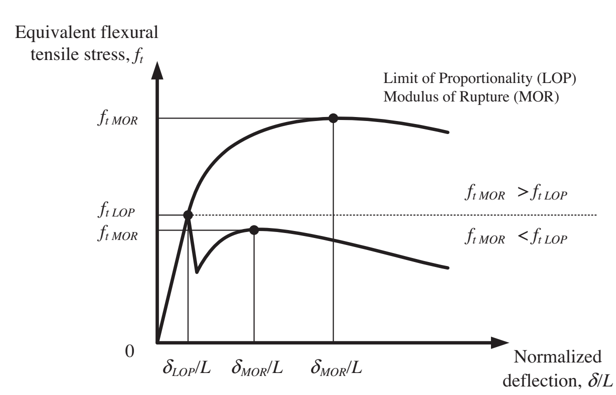

Fig. 2. Typical flexural behavior of FRCCs.