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Toughness indices of fiber reinforced concrete subjected to mode II loading

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ABSTRACT: This paper reports on some studies on development of test geometry and testing procedure to determine the toughness indices of fiber reinforced concrete in Mode II loading. The proposed test geometry consists of a beam, 150mmx150mmx600mm, with two-2mm wide and 15mm deep all-round notches. Tests were conducted to achieve Mode II fracture in plain and fiber reinforced concrete (FRC) beams. Steel fibers (length = 25mm and aspect ratio = 44.6) were randomly distributed in concrete at varying fiber volume fractions of 0, 0.5, 1.0 and 1.5%. The failure was observed to be essentially in pure shear along the predefined fracture plane. Plain concrete was observed to fail at an equivalent shear strain of 0.5%, while the shear strain was 8.0% in fiber reinforced concrete. The strength and toughness of concrete in Mode II loading have been improved by the addition of steel fibers to concrete. The shear strength of FRC increases as the volume fraction of fibers increases. Similar trend has been observed with the toughness of concrete.

1 INSTRUCTION

Concrete is used extensively in civil engineering construction practice owing to its low production cost, formability, and much desirable response. Despite its several merits, it is weak in tension with less cracking resistance. The deficiency of concrete in tension could be improved to a large extent if it is reinforced with fibers (Wu et al. 2000). The fibers when randomly distributed throughout the volume of concrete at relatively smaller spacing could achieve uniform resistance to stresses in all directions making it as a homogenous and isotropic material (Samir et al. 1992). Thus, the fibers randomly distributed in plain concrete alter the brittle characteristics of concrete in to ductile. The studies on fracture behavior of concrete in Mode II loading effects are limited. Fracture mechanics of concrete (FMC) studies the behavior of quasi-brittle materials in the presence of cracks and crack like defects, which offers convenient means to measure the fracture strength or toughness of material (Tamrakar 1999). In brittle materials, the applied elastic energy is assumed to be consumed as surface energy to form new crack surfaces with meager dissipation due to fracture processes (Griffith 1921). In ductile materials, the energy is dissipated as plastic energy to form plastic zone in front of the crack tip, which is significantly larger than the elastic surface energy (Dugdale 1960, Barrenblatt 1962).

In quasi brittle materials like concrete, a large fracture process zone (FPZ) is formed in front of a crack like defect that consumes huge amount of the total energy. FPZ is also a source of size dependency of many fracture parameters of concrete (Bazant and Kazemi 1990). Additional toughening mechanisms arise due to the addition of fibers including fiber bending and internal work of fiber debonding and fracture (Beaudoin 1990). Other mechanisms such as fiber bridging, fiber pull out and/or fiber debonding in concrete can increase the fracture toughness (Li et al. 1995, Mindess 1983).

2 MODE II TEST GEOMETRY

2.1 *Iosipescu shear test*

Iosipescu shear test (Iosipescu 1967) could achieve pure shear at the mid span as shown in Figure 1. The ends of the test specimen are restrained against rotation by loading fixture, while subjecting the specimen to shear loading. Iosipescu test is more advantageous, and was also found that by cutting 90^0 notches on each edge, the shear-stress distribution within the specimen could be altered from parabolic to constant distribution between the two notches. Contrary to the expectations, no stress concentration is induced by the notches, at least for isotropic materials, as the notches are parallel to the stress directions at that point. Therefore, the shear stress 'τ' for the test shown in Figure 1 is the shear force divided by the net cross-sectional area, i.e.,

$$\tau = \frac{P}{bt} \tag{1}$$

where b = net width between the two notches and
t = thickness of the test specimen.

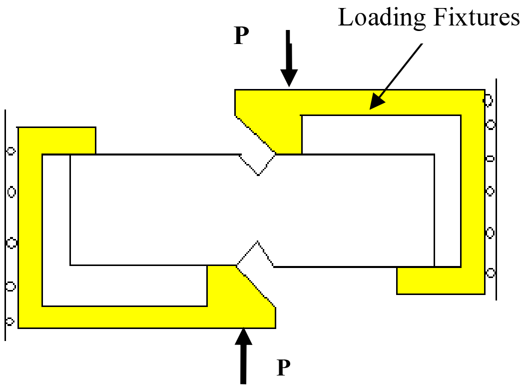

Figure 1. Iosipescu shear test.

2.2 *Asymmetrical four-point bend (AFPB) test*

The Slepetz's method (Slepetz 1978) termed as the Asymmetrical Four-Point Bend (AFPB) Test is very similar in principle to the Iosipescu test. They are essentially the same except the difference in set up as shown in Figure 2.

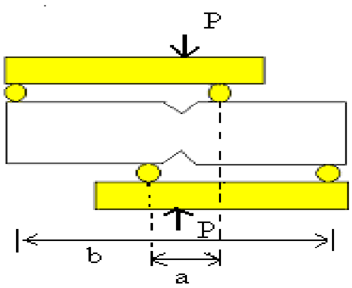

Figure 2. AFPB test set-up.

The mid length shear loading, V is now dependent on the distance between the forces, i.e.

$$V = P\frac{(a-b)}{(a+b)} \tag{2}$$

Instead of Iosipescu's expression V = P, this may not be a serious disadvantage of AFPB configuration, as the loading points of the fixture can be accurately determined. However, the cylindrical load points cause local crushing on the edges of the composite specimens, requiring the use of reinforcing tabs. Both the methods are applicable to both isotropic and anisotropic solids, including metals, polymer, unidirectional and angle-plied laminates, as well as randomly oriented fiber-reinforced composites. However, these tests were never attempted for testing of concrete.

2.3 *AFPB test as applied to concrete*

The test adopted for the determination of fracture properties of concrete by Bazant et al. (1986) was similar to AFPB test. Symmetrical notched beams of concrete and mortar, loaded near the notches by concentrated forces to produce a concentrated shear zone were tested as shown in Figure 3.

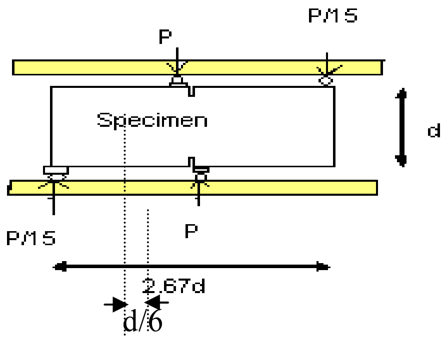

Figure 3. Bazant test set-up.

The test geometry was adopted to verify whether the shear (Mode II) failure occurs or not. It was found to be positive. The stress field as well as the strain and strain energy density fields near the fracture front do not govern the direction of fracture propagation. But, the direction of fracture propagation is governed by the maximum energy release rate criterion. The analytical studies (FE studies) also confirmed the maximum energy release rate criterion that governs the direction of crack propagation.

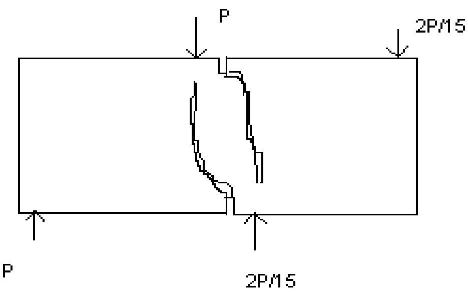

Figure 4. Cracking in wide shear zones.

However, the crack band propagation was deviated sideways when the width of the shear zone was increased as shown in Figure 4. When the shear zone was narrow, the crack propagated in the vertical direction showing pure shear fracture.

2.4 *Push-off test*

Z-type push-off test is the most popular one adopted for the direct shear test. It consists of two L-shaped blocks that are connected through a ligament along which the shear loading is applied, as shown in Figure 5. Several attempts have been made so far on different types of push-off tests by varying the specimen dimensions. To avoid cracking of concrete outside the shear plane, many attempts have been made using side grooves (which may result in a two-dimensional crack front). Van Mier (1997) found that the failure mechanism was governed by splitting-tension rather than shear in plain concrete. Hence, this geometry and the test method cannot be used to predict the pure shear failure in plain concrete. To avoid cracking outside the shear plane, attempts have resorted to placing of reinforcing bars in the L-shaped blocks as shown in Figure 5. The initial cracks occurred at the load levels between 50 and 75% of the peak loads. The cracks were oriented diagonally at an inclination of between 15 and 45 degrees to the shear plane. The ultimate failure occurred due to formation of crack band along the shear plane.

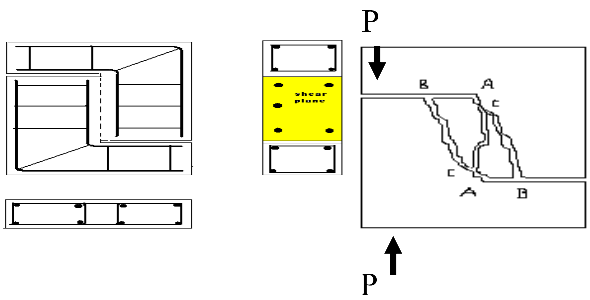

Figure 5. Schematic of the Push-off specimen.

2.5 *JSCE SF-6 Method*

The Japan Society of Civil Engineers (JSCE) proposed a standard method SF-6 (1990) with an improvement of the z-type push-off test. In such test, the stress field remains substantially in pure shear, and hence a more reproducible shear response is obtained. However, not much of work has yet been made to measure the Mode II properties of FRC using JSCE SF-6 method. The test specimen is a beam of cross section 150mm x 150mm and 500mm length. The test set up is shown in Figure 6. The load is applied through a loading block with two blunt steel edges 150mm apart. The beam is supported on another rigid block over a pair of blunt steel supports that are 155mm apart with 2.5mm gap in between the loading and the supporting edges as shown in Figure 6, where the shear failure is expected. The

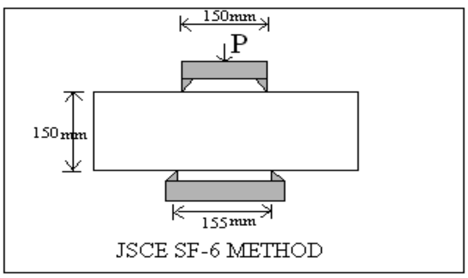

Figure 6. JSCE SF-6 Test Method.

contact area of the supports with concrete is small and no traces of local crushing of concrete were observed with these supports.

2.5.1 *Trial tests as per JSCE SF-6 method*

Trial tests were performed according to the JSCE SF-6 procedure on plain and fiber reinforced concrete. The failure of concrete is shown in Figure 7. The failure plane was deviated from the predetermined narrow zone under the direct shear load. Therefore, the JSCE test could not predict the ideal shear failure. Hence, some modifications are required in the present form of test geometry of JSCE SF-6 to achieve the shear failure and to determine the concrete shear properties.

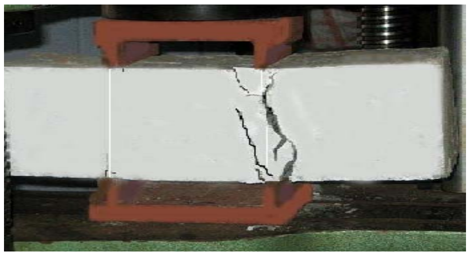

Figure 7. JSCE SF-6 test geometry and failure.

The purpose of the present attempt is to propose modifications for JSCE SF-6 test method for quantifying the material properties of steel fiber reinforced concrete (SFRC) in pure shear.

3 PROPOSED TEST GEOMETRY

Knowing the merits and demerits of JSCE SF-6 method, the test geometry was altered by providing with all-round notches in the pure shear region of the specimen. Several attempts have been made to achieve the final form of test geometry. In the first attempt, two notches of 2mm width and 6mm depth were formed on two opposite vertical faces of the beam in the shear load zone of 2.5mm width between the loading and the supporting edges. The failure was deviated from the ideal shear. In the second attempt, notches of 2mm width and 10mm depth were formed. In the third attempt, two 15mm deep notches were formed. In all the three attempts, the failure was deviated from the anticipated shear failure plane. In the fourth attempt, a 2mm wide and 15mm deep all-round notch was formed on all the faces of the beam. The final form of the test geometry and the mode of failure in the test beam are shown in Figure 8. It was found that the failure was in pure shear i.e. Mode II mode along the predetermined plane coinciding with the pre-notches. Unlike in the push-off and other types of test geometry, the proposed geometry could maintain its integrity and intactness in FRC. Hence, the proposed geometry is certainly an improvement over the JSCE SF-6 method, which will be proved to be effective to determine the fracture properties of FRC under Mode II loading.

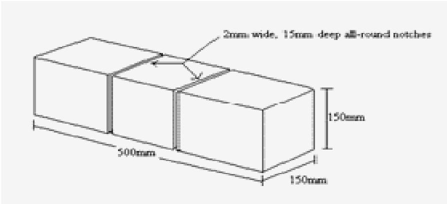

Figure 8. Proposed geometry and failure mode.

4 RESEARCH SIGNIFICANCE

Several attempts have been made to study the behavior of fiber reinforced concrete. However, the studies on Mode II fracture properties are limited. The cracking of concrete in pure shear i.e. Mode II fracture is of considerable importance, particularly of the causes of brittle failure and their controlling measures. Recently, the effectiveness of fibers in improving the shear performance of structural concrete has been pronounced. The steel fibers control the shear deformations effectively at all stages of loading (Bazant and Kazemi 1990). Since the fracture processes of fiber reinforced composites are complex, their fracture studies in Mode II are important.

5 EXPERIMENTAL STUDIES

5.1 *Casting of specimens*

Ordinary Portland cement was used for this study. Natural river sand passing through 2.36mm sieve with fineness modulus of 2.67 was used. 20mm size crushed granite was used. Steel fibers of 0.53 mm diameter, 25 mm long and aspect ratio of 44.6 were used. Potable water was used for curing and mixing of concrete. The concrete mix proportions are given in Table 1.

Table 1. Mix proportions.

S.No.	C : FA : C.A	w/c ratio	V_f (%)
1	1:2:3	0.45	0.0
2	1:2:3	0.45	0.5
3	1:2:3	0.45	1.0
4	1:2:3	0.45	1.5

The constituent materials were thoroughly mixed in a machine mixer to produce a uniform mix. Fibers were randomly distributed up to very end to ensure uniform concrete. Care has been exercised to minimize balling of fibers. Fresh concrete was poured in steel moulds. External vibration was done for proper compaction. From each concrete mix; three 150 x 150 x 500 mm prisms for testing in direct shear, three 150 x 150 x 600 mm beams for testing in flexure and six 100 mm diameter and 200 mm long cylinders for compressive strength and split tensile strength were cast. Central notches of 2mm width and 75mm depth were formed in the flexure beams of size 150mm x 150mm x 600mm while casting. The shear specimens described above were cast for determining the fracture properties of FRC in Mode II. After 24 hours, the beams were demolded and cured for 28 days. After curing, the specimens were air dried before testing.

6 RESULTS AND DISCUSSION

6.1 *Failure pattern of the specimens*

The failure of concrete was in ideal Mode II failure in the predetermined plane coinciding with the pre-notches.

6.2 *Load-slip response*

Typical load-slip curves under direct shear loading in all the plain and FRC specimens with different volume fraction of steel fibers show that the modified JSCE-SF6 method is capable of characterizing FRC under shear loading. The slip was measure4de in the direction of the movement of the central constant shear region with reference to the concrete between the loading point and the supporting point. The slip was monitored using dial gauges mounted to a stationary member. The load-slip response is linear up to the first cracking, then tends to become nonlinear up to the peak load followed by a sudden drop and then is nearly horizontal exhibiting significant ductility.

6.3 *Fracture Toughness*

The fracture toughness in Mode II failure, K_{IIc} was determined from the load-slip curves. From the area under the load-slip curves, which is called the work of fracture, the K_{IIc} value was computed. The test results are shown in Table 2. Then fracture energy per unit area of surface in Mode II, G_{II} was computed using the formula,

$$G_{II} = \frac{W_{Fs}}{A_{eff}} \tag{3}$$

where A_{eff} = effective area of cross section of the specimen. W_{Fs} = work of fracture in Mode II, calculated as the area under the load-slip curve. Then the critical stress intensity factor or fracture toughness, K_{IIc} was computed using the formula,

$$G_{II} = \frac{\left(1-\nu^2\right)K_{IIC}^2}{E} \tag{4}$$

where E = young's modulus of the concrete = $5000\sqrt{f_c}$ and μ = Poisson's ratio = 0.125, f_c = cylinder compressive strength of concrete. The specific toughness is defined as the energy per unit strength of concrete, was also computed. The specific toughness is given by W_{Fs}/f_c, whose values are shown in Table 2.

The fracture toughness, K_{IIc} is 188.7 N/mm$^{1.5}$ in plain concrete. The fracture toughness of fiber reinforced concrete with volume fractions 0.5, 1.0 and 1.5% are 603.3 N/mm$^{1.5}$, 743.3 N/mm$^{1.5}$ and 855.64 N/mm$^{1.5}$ respectively. The fracture energy per unit cracking area, G_{II} increases significantly with increase in the volume of steel fibers. Further, the fracture toughness increases as the volume fraction of fibers in the concrete increases.

6.4 *Ultimate shear strength*

The ultimate shear strengths with different volume fraction of steel fibers was computed, assuming elastic response using the following formula

$$\tau_{max} = \frac{P_{max}}{A_{eff}} \tag{5}$$

Where P_{max} = peak load on the test specimen on one plane, and A_{eff} = effective area of cross section of the test specimen. Three specimens were tested to obtain the shear strength. The ultimate shear strength obtained at different volume fraction of fibers is given in Table 2. The correlation constant, k between the ultimate shear strength and the compressive strength of concrete is given by

$$k = \frac{\tau_{max}}{\sqrt{f_c}} \tag{6}$$

Table 2. Strength and fracture properties of SFRC

S.No	P_{max} (kN)	δ_{max} (mm)	τ_{max} (MPa)	f_c (MPa)	f_t (Mpa)	$\tau_{max}/\sqrt{f_c}$	W_{Fs} (N-m)	W_{Ff} (N-m)
1	98	0.77	3.4	21.0	1.79	0.74	44	
2	118	8.50	4.1	21.4	2.19	0.89	446	12
3	135	9.75	4.7	22.0	2.31	1.0	668	15
4	150	10.8	5.2	22.0	2.35	1.11	885	22

It can be noticed that the shear strength increases as the fiber volume fraction of increases. The ultimate shear strength can be expressed as a function of fiber volume fraction

$$\tau_{max} = \tau_0 + K\,V_f^n \tag{7}$$

Where τ_0 = shear strength of plain concrete, K = constant and V_f = volume fraction of steel fibers as percentage. The shear strength of FRC is given by

$$\tau_{max} = \tau_0 + 1.3V_f^{0.896} \tag{8}$$

Where τ_0 depends upon the mix proportions of concrete, thus indirectly depends on the compressive strength of concrete.

6.5 *Fracture toughness vs. fiber volume fraction*

The normalized fracture toughness, K_{IIc} with respect to the compressive strength of concrete, f_c was estimated in FRC. The normalized fracture toughness (K_{IIC}/f_c) values are 8.986 mm$^{0.5}$, 28.19 mm$^{0.5}$, 33.79 mm$^{0.5}$ and 38.89 mm$^{0.5}$ in concrete with fiber volume fractions of 0.0, 0.5, 1.0 and 1.5% respectively. Significant increase in the toughness due to the addition of fibers can be noticed. As the fiber volume fraction increases the fracture toughness also increases. The failure in plain concrete was sudden and catastrophic. The ultimate strain in plain concrete was 0.5 %, while it was 8.0% with the addition of fibers. The fibers in concrete maintained integrity and reduced the brittleness of concrete.

6.6 *Shear toughness indices*

As per ASTM C-1081, the flexural toughness index is defined as the ratio of the energy required to deflect a beam to a specific deflection, expressed as multiples of the first crack deflection. For example, toughness index I_5 is defined by the equation

$$I_5 = \frac{Area\ under\ the\ 'load\ -\ deflection\ '\ curve\ upto\ 3\delta}{Area\ under\ the\ 'load\ -\ deflection\ '\ curve\ upto\ \delta}$$

where δ = deflection at first crack.

The indices I_{10} and I_{20} are the ratios of the area under the load deflection curves up to 5.5 and 10.5 times the first crack deflection divided by the area up to the first crack deflection respectively. The JSCE SF-6 does not specify any procedure to calculate the shear toughness indices, the procedure for calculating the flexural toughness indices by ASTM was adopted. The indices are shown in Table 3. The toughness indices increase as the volume fraction of fibers increases.

Table 3. Fracture toughness values of SFRC.

S. No	G_I (N/mm)	G_{II} (N/mm)	K_{IIC} ($N/mm^{1.5}$)	Sp. toughness (mm^3)X10^3	I_5	I_{10}	I_{20}
1		1.53	188.7	2.1			
2	1.07	15.49	603.3	20.84	3.7	5.8	8.6
3	1.33	23.19	743.3	30.36	5.0	7.43	11.7
4	1.95	30.73	855.64	40.23	5.9	10.1	15.7

6.7 *Shear toughness vs. flexural toughness*

It has been observed that the Mode II fracture energy is about 15 times higher than the Mode I fracture energy. Different from flexural (Mode I) crack propagation, the shear (Mode II) crack propagation is accompanied by compression after the peak load. It could be due to the combined action of shear, compression and aggregate interlocking. Hence, the Mode II fracture energy is much more than Mode I fracture energy. Table 3 shows the test results.

7 CONCLUSIONS

The modified geometry in this study is an improvement over the JSCE-SF6 method for obtaining the characteristics of FRC under Mode II loading. The addition of steel fibers in plain concrete increases the shear strength and the shear toughness. The shear strength of FRC increases as the volume fraction of fibers increases. Similar trend has been observed with the toughness of concrete. The ultimate shear strain in plain concrete was 0.5%, while it was 8.0% in FRC. The Mode II fracture energy is about 15 times higher than the Mode I fracture energy in FRC. The toughness indices increase with increase in fiber content.

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