ACI MATERIALS JOURNAL TECHNICAL PAPER

Title no. 87-M48

Experimental Determination of Tensile Behavior of Fiber Reinforced Concrete



by Youjiang Wang, Victor C. Li, and Stanley Backer

With reported improvements in tensile behavior of concrete due to fiber reinforcement, considerable interest has been generated in tensile testing techniques for cementitious composites. Such methods are reviewed and a novel method for direct tensile tests on fiber reinforced concrete (FRC) is described. The method requires only a simple loading fixture yet gives satisfactory test results. The results of tensile measurements are reported for various synthetic FRC with mortar matrix. It is expected that direct tensile test of FRC can be widely performed by using this method.

Keywords: fiber reinforced concretes; measurement; splitting tensile strength; stiffness; **synthetic fibers; tensile properties;** tensile strength; **tension tests.**

Fiber reinforced concrete (FRC) has superior tensile properties, particularly ductility, over plain concrete. Studies have indicated that the tensile stress-crack separation (σ-δ) curve is the best alternative to characterize the tensile behavior of FRC.[1,2] In principle, the response of an FRC structure can be predicted from the σ-δ curve which describes the material constitutive relation along the matrix cracks in the structure, together with the stress-strain (σ-ϵ) relationship which applies elsewhere in the structure. Although the stress state in the structure may be biaxial or triaxial, it is generally assumed that the σ-δ curve can be determined from a uniaxial tensile test. This assumption is considered justifiable since concrete is a nonyielding material and the difference between plane stress and plane strain is insignificant for concrete.[3] However, experimental verification of this assumption is still needed.

In this study, an improved method was developed for direct tensile testing of FRC. This method is relatively simple and gives satisfactory results. The tensile properties of mortar matrix FRC containing aramid, polyethylene, polypropylene, and a combination of aramid and polyethylene fibers were studied using this direct tensile test. The test results will be briefly described.

RESEARCH SIGNIFICANCE

Tensile behavior is a fundamental property of FRC. It is important for FRC structural design and useful for optimization of FRC with respect to reinforcement parameters. Methods of direct tensile tests currently available are generally limited due to their requirement of complicated equipment. The method introduced here is performed on widely available machines with a simple loading fixture. It can be broadly adopted in FRC studies.

REVIEW OF DIRECT TENSILE TEST METHODS

Because of the brittle nature of concrete, valid direct tensile testing of concrete and FRC is always difficult to carry out, for the accuracy of the direct tensile test is strongly dependent on test conditions. Presently, no standard methods are available for the direct tensile test. Due to the importance of the tensile behavior of FRC and concrete, many direct tensile tests of these materials have been attempted, using different designs of loading grips.[4-15] Indirect methods of measuring the σ-δ curves have also been attempted using other more stable test configurations.[16-20]

To insure a stable uniaxial tensile test, the testing equipment should satisfy the following basic requirements:

1. The testing fixture, including the testing machine, loading grips, and junctions between them, must be stiff enough to avoid unstable unloading after the specimen peak load is reached.
2. Misalignment of the specimen should not be introduced by the loading grips to avoid imposition of an unknown initial stress field on the specimen;
3. The testing fixture should have high rotational rigidity to prevent bending strains in the specimen and thus to insure a uniform strain across the specimen.

These requirements are discussed in the following sections.

ACI Materials Journal, V. 87, No. 5, September-October 1990.
Received Aug. 18, 1989, and reviewed under Institute publication policies.

Pertinent discussion will be published in the July-August 1991 *ACI Materials Journal* if received by Apr. 1, 1991.

Youjiang Wang is Assistant Professor in the School of Textile and Fiber Engineering at the Georgia Institute of Technology, Atlanta. He received his PhD in Mechanical Engineering from the Massachusetts Institute of Technology in 1989. His interests include fiber reinforced concrete, composite materials, and engineered fibrous structures.

placement as the feedback signal to control the machine actuator, this equipment, in principle, can maintain a constant rate of specimen crack opening; therefore, all of the loading equipment and portions of

[redacted]

opening displacement gage with a gage length of 12.7 mm to provide the feedback signal (specimen dimension and loading fixture to be described in a later section). Because of insufficient sensitivity of the displacement sensor and/or insufficient accuracy in actuator movement, all such tests performed were unstable.

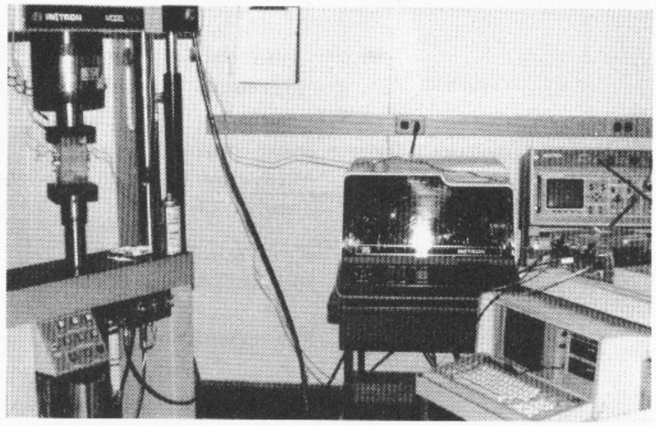
Specimen alignment and equipment rotational stiffness

Specimen misalignment introduces unknown initial stresses in the specimen, which may affect the accuracy of test results significantly. Eccentric mounting of specimens induces bending stresses, which can be effectively reduced by use of hinge joints that allow free bending in different directions. Almost all testing fixtures used for direct tensile tests have such joints. The fixture developed at the Delft University of Technology, however, has no flexible joints, and specimen-end rotations are prevented by a guiding system (Fig. 1). Misalignment problems in the Delft system are presumably solved by gluing the specimen to the loading platens.

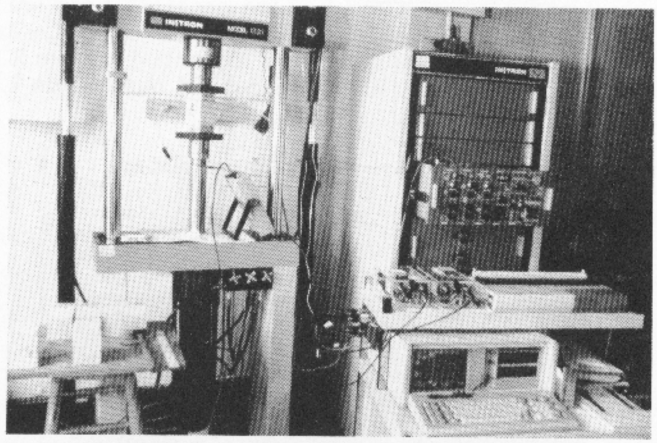
Although the use of hinge joints can *reduce* the initial bending stress, it also allows the free rotation of specimen ends and therefore allows the development of bending strains in the specimen during testing. The failure process of a uniform (unnotched) FRC or concrete specimen in direct tension usually involves, in sequence, uniform linear elastic deformation, microcracking over the specimen, concentration of microcracks near a plane, formation of a macrocrack in the plane, crack propagation to the whole plane, and pull-out of aggregates and/or fibers bridging the crack. It is unlikely that the macrocrack will always start from the center of the cross section and propagates axisymmetrically over the plane. Particularly in notched specimens commonly used for direct tensile tests, the crack is more likely to start from the existing notches. The stress field across the specimen during tensile testing is therefore nonuniform. For this reason and in view of the fact that all specimens contain inhomogeneities, bending strains could be introduced if no restrictions on specimen end rotation are imposed; therefore, the test is no longer a true *uniaxial* tensile test in which, by definition, the strain field in the cross-sectional plane of interest should be uniform.

Although symmetric deformation in tensile tests of concrete using hinge joints has been reported by Gopalaratnam and Shah,[11] they have also noted unsymmetrical crack formations which make it necessary to use the average displacement across the two notches in opposite sides of the specimen as the feedback signal. Nonuniform deformation has also been observed by others[12] and is believed to be a more general mode of deformation for tests conducted with such loading fixtures. It is therefore desirable that test results associated with high deformational nonuniformity be so indicated.

Deformational nonuniformity can be significantly reduced if the loading fixture has very high stiffness



(a)



(b)

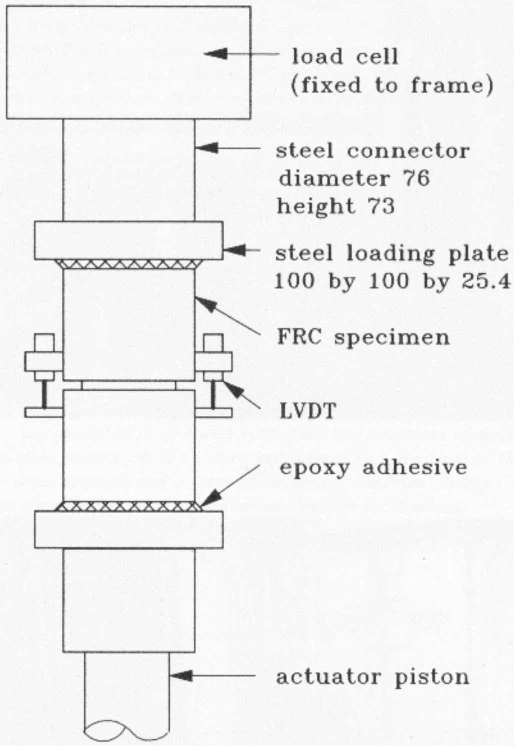
Fig. 2 — Setup of the direct tensile test: (a) on a computer-controlled Instron machine; (b) on a manually controlled Instron machine

against specimen end rotations. However, even with the Delft fixture that includes the guiding system, such nonuniformity has been reported for long specimens of lightweight concrete, and found to be related to "bumps" (sudden load drops) in the stress-displacement curves.[12] The nonuniformity is expected to be less for normal weight concrete, and it decreases with the decrease of specimen length used in the test.

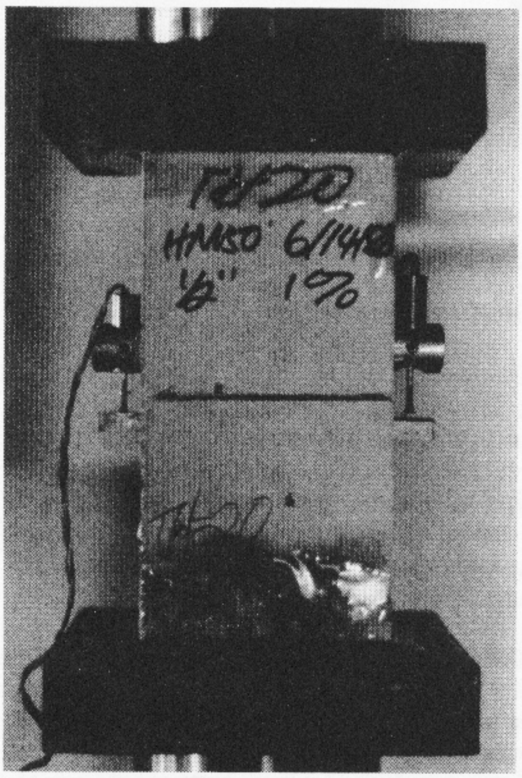
EXPERIMENTAL PROCEDURES FOR THE DIRECT TENSILE TEST

Setup and description

In this study, a modified method of FRC direct tensile testing has been developed. The test setup is shown in Fig. 2. The test has been performed on two testing machines, both servo-hydraulic Instron machines of 100 kN tension/compression capacity, one computer controlled and the other manually controlled. The loading fixture consists of a pair of heavy steel plates 25.4 mm thick, tightly connected to the testing machine, with one plate bolted to the load cell and the other to the actuator piston (Fig. 3). The test specimen is glued to the loading plates with fast-curing epoxy adhesive. By eliminating "soft" connections between the



(a)



(b)

Fig. 3 — Details of the loading fixture. (a) schematic illustration; (b) photograph (dimensions are in mm)

specimen and the machine, this setup takes full advantage of the stiffness of the machine frame to minimize the release of strain energy in the testing fixture and to restrain the end rotations of the specimen. In addition, the in situ curing of the adhesive excludes nonuniform initial strains in the specimen.

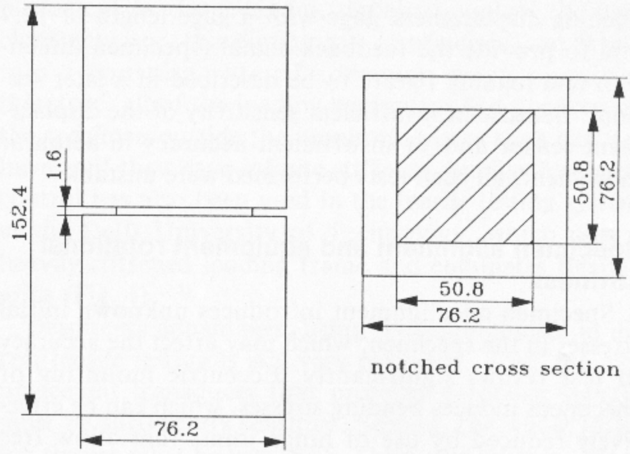


Fig. 4 — Dimensions, mm, of direct tensile test specimens

This test fixture is very versatile — as it can readily use specimens with different geometries and dimensions. In this study, all the tests were done with specimens of the same size, as shown in Fig. 4.

Two LVDTs (linear variable differential transformers), both with a displacement range of 5.08 mm, were used to monitor the crack-opening displacement. The LVDTs were mounted on two opposite sides of the specimen with aluminum holders glued to the specimen surface. The nominal measuring gage length was 12.7 mm. Signs of load, crack openings of the two sides, and the machine piston displacement were recorded by a microcomputer.

The test was performed at constant speeds of machine piston movement. The method of loading was found satisfactory to provide a stable loading condition for most FRC tests. Fig. 5 shows time-domain signals of load, crack openings of the two sides, and the machine piston displacement for a test of FRC containing 1 percent 12.7 mm high-strength polyethylene fibers and 1 percent of 12.7 mm aramid fibers (Mix H1), from which it can be seen that the test was stable, with no sudden load drops experienced as the crack opened. Comparison between the crack openings measured by the two LVDTs also indicated no noticeable bending effect in the specimen.

However, due to insufficient machine accuracy, the tests of plain mortar specimens were found to be unstable. Because of the brittleness of mortar specimens, the machine must be able to position the actuator piston with an accuracy of about 1 μm to obtain a stable unloading part of the σ-δ curve. The Instron machines used for the test, designed for dynamic testing rather than accurate static testing, did not have such accuracy. Clearly, a more accurate testing machine is required for plain mortars and would be desirable as well for tensile tests of FRC.

The direct control of machine displacement is easier to perform than the feedback control of crack opening, although the latter may be more desirable. Direct control eliminates the need of high-sensitivity displacement transducers and permits stable tests with a less accurate machine.

The simplicity of the loading fixture required by this method could make the direct tensile test of FRC a widely performed laboratory test. However, to insure a high success rate, precautions are needed to avoid failure of the specimen, or failure of the adhesive during its curing prior to testing. By following the established test procedures, premature specimen failure basically has been eliminated in this study. The test procedures are detailed in the next section.

Specimen preparation

A mortar matrix, composed of Type III cement, mortar sand, and water (weight ratio = 1:1:0.5) and reinforced with various synthetic fibers, including two aramids, high-strength polyethylene, and undrawn polypropylene. Fiber length L_f, diameter d_f, and volume fraction V_f will be given later with the test results. Details on materials, mixing, and curing of FRC specimens can be found elsewhere.[21,22]

Specimens for the direct tensile tests were cast in plexiglass molds with inner dimensions of 76.2 x 76.2 x 279.4 mm. Between 5 and 10 days after casting, the specimens were removed from the curing tank for surface grinding and notch-cutting. Each specimen was cut into two parts, a longer one with a length (about 155 mm long) for the direct-tensile test, and a shorter one (about 120 mm) for the splitting-tensile test. The free surface of the cast direct-tensile test specimen was ground to smoothness with a water-cooled grinding machine to insure precise notch-cutting. The specimen cast end, opposite to the cut end, was also ground to remove the 3 mm thick top layer. It is necessary to remove the weak surface layer for the specimen to be firmly glued to the loading plate. Notches 12.7 mm deep were cut in all four sides of the specimen in the middle cross section with a 1.6 mm thick diamond saw. After grinding and notch-cutting, the specimens were returned to the curing tank. All the tests were performed at a specimen age of 14 ± 1 days. The specimens were removed from the water tank the day before testing, and left to air-dry in the laboratory.

Nominal dimensions of the tensile specimens are shown in Fig. 4. Actual areas of the net specimen cross sections were measured after the tests and used to calculate stresses.

Test procedures

Machine command setting — The machine for the tensile test was set at position control (also called stroke control). The command signal for controlling the piston movement is shown in Fig. 6. Stage I sets the starting position of the piston by following a ramp signal. After the full stop of the ramp is reached, the machine is held in that position for specimen-mounting and glue-curing (Stage II), which takes about 1 hr. The actual test is performed in Stages III and IV. The speed in Stage III is very low, so that details of ascending and

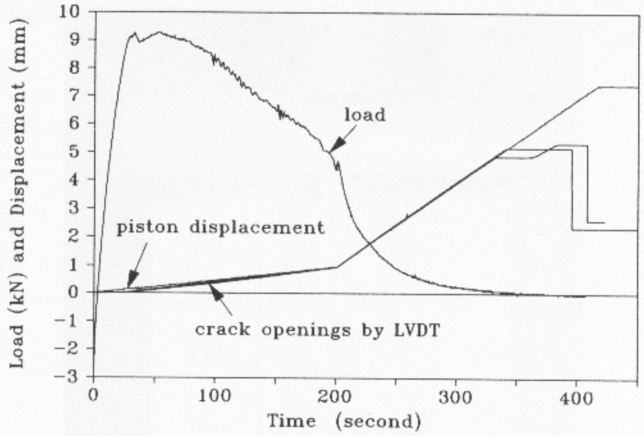


Fig. 5 — Time domain signals of load, crack openings of the two sides measured by LVDTs, and the machine piston displacement for a test of FRC containing 1% 12.7 mm high-strength polypropylene fibers and 1% 12.7 mm aramid B fibers (mix H1)

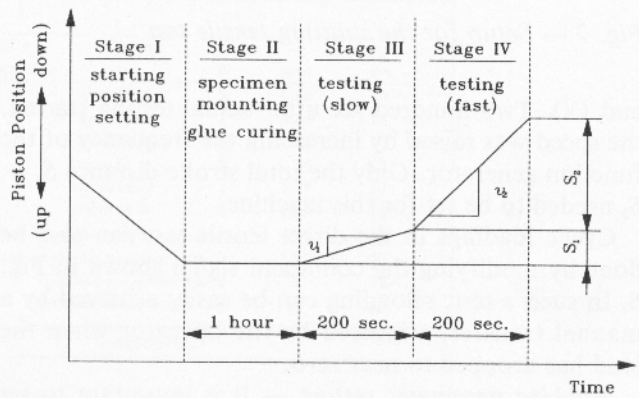


Fig. 6 — Command signal versus time for the direct tensile test

initial descending parts of the σ-δ curve can be captured. Once the crack is opened to a certain width, the test is less sensitive to loading speed; therefore, a fast speed is used in Stage IV to complete the test. The time durations used in this study for these stages are indicated in Fig. 6. The speed and stroke for Stage III were v_1 = 0.005 mm/sec and S_1 = 1 mm, completed in 200 sec. The stroke distance for Stage IV was selected based on fiber length and/or experience, so that the specimen could be separated. The speed for this stage was chosen to complete the test stage in about 200 sec.

It is important to note that the command signal is a *continuous* function of time. Any interruption will almost certainly cause the specimen to fail prematurely. In the computer-controlled Instron machine, the command signal was programmed, using the general program, into three blocks: one block for Stages I and II, and one block each for Stages III and IV. Manual transfer was selected to start Stage III, the actual testing. In the manually controlled Instron machine, a double ramp control was used, by first moving the piston up (Stage I), holding it there (no action required, Stage II), then reversing the ramp for testing (Stages III

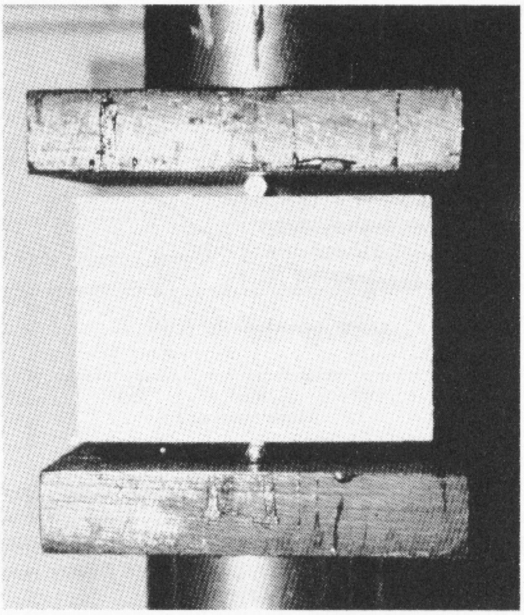


Fig. 7 — Setup for the splitting tensile test

and IV). Two hundred sec after actual testing started, the speed was raised by increasing the frequency of the function generator. Only the total stroke distance $S_1 + S_2$ needed to be set for this machine.

Cyclic loadings in the direct tensile test can also be done by modifying the command signal shown in Fig. 6. In such a test, reloading can be easily achieved by a manual transfer, triggered by the operator when the load has dropped to near zero.

Machine parameter setting — It is important to set the machine parameters (controller gain, time constant, etc.) properly so that machine piston drift is minimized and the actual machine movement can follow the command signal closely. Unfortunately, the optimal section of these parameters depends on the individual machine, or less desirably, on the stiffness of the specimen, which varies during testing for FRC. A rule of thumb is to choose the parameters with the highest gain that give a "stiff" machine response but without excessive overshoot when no specimen is mounted on the machine, then to decrease the gain by about 5 to 10 percent to avoid machine oscillation.

The parameters used for this study were, for the computer-controlled machine using its general program: gain = 50, time constant = 14, and mass compensation = 10. For the manually controlled machine: gain = 9 and integration = 9 (for the stroke controller).

Specimen mounting — The specimen was glued to the loading plates with a fast-curing epoxy adhesive that developed full strength in about 1 hr after mixing at room temperature. The epoxy and the hardener must be mixed thoroughly and uniformly to insure rapid hardening and high strength.

The specimen was first glued to one plate on a table. To control the glue thickness, four wire segments of 0.5 mm diameter x 2 mm length were first glued to the plate with instant glue (the one often used for foil strain-gage mounting), then the epoxy mix was applied to the plate. After removing the air bubbles in the epoxy, the specimen was placed at the center of the plate, sitting on the wire segments. When the glue hardened in about 15 min, the loading plate with specimen was tightened to the machine load cell, and the other plate was tightened to the actuator piston. After the machine was turned on and Stage II of the loading sequence (Fig. 6) was reached, the epoxy mixture was applied to the lower loading plate attached to the piston to close the gap between the specimen bottom and the plate with epoxy to about 0.5 to 1 mm. This was achieved on the computer-controlled machine by moving the machine top-crosshead down and locking it in position, and in the manually controlled machine by raising the piston with the zero-suppression control. An hour later, the actual testing (Stages III and IV) was performed.

After testing, the loading plates with broken specimens were heated on an electric stove and cleaned when the epoxy became soft. For health reasons, this operation should be done under a ventilation hood to prevent inhalation of the burning fumes.

To test multiple specimens continuously, at least two pairs of the loading plates are needed.

Data acquisition

Voltage signals of load, crack openings of the two sides measured by LVDTs, and the machine piston displacement were recorded by a portable personal computer via an analog/digital conversion board installed in the computer. Unkel Scope, a software program developed at the Massachusetts Institute of Technology, was used to control the data sampling. The sampling interval per channel was 0.2 sec at 5 Hz, and the number of samples taken were 2048 per channel with a total sampling time of 410 sec.

Splitting tensile test

Splitting tensile tests were also performed to measure the cracking strength of FRC. The specimens, which measured 76.2 × 76.2 × 120 mm, were prepared with the direct tensile specimens. The test setup is shown in Fig. 7. The specimen was loaded with a pair of hexagonally cross-sectioned rods, the side width of which was 5 mm. The test speed was 0.005 mm/sec. The load at matrix cracking P, identified from the load-displacement plot, was used to calculate the splitting tensile stress σ_s from

$$\sigma_s = \frac{2P}{\pi A} \tag{1}$$

where A is the area of the specimen cross section between the loading rods.

TEST RESULTS

FRC mixes listed in Table 1 were tested in direct tension and splitting tension. For each mix, six specimens

Table 1—Tensile strength and fracture energy of FRC

					Direct tensile		Splitting tensile		Fracture energy	
Fiber	Mix no.	V_f, percent	L_f, mm	d_f µm	MPa	Coefficient of variation, percent	MPa	Coefficient of variation, percent	kJ/m²	Coefficient of variation, percent
None	0	0	—	—			1.85	8.6		
Aramid A	K1	2	6.35	12	3.96	11.9	3.65	9.3	1.31	13.4
Aramid B	T1	1	6.35	12	3.31	5.0	3.26	7.7	1.42	17.7
	T2	2	6.35	12	3.11	6.3	3.58	8.0	1.28	13.4
	T3	3	6.35	12	3.65	12.2	4.15	12.1	1.87	18.2
	T4	1	12.7	12	3.49	10.9	3.66	4.1	2.13	30.9
	T5	2	12.7	12	4.17	4.1	3.96	7.7	4.36	11.0
High-strength polyethylene	S1	1	12.7	38	2.39	8.2	2.84	7.2	5.98	10.3
	S2	2	12.7	38	2.70	1.9	2.82	9.1	5.62	16.1
Undrawn polypropylene	P1	2	5	22	2.21	9.5	2.58	9.6	1.44	8.8
	P2	2	10	22	2.14	13.3	2.02	7.8	4.58	12.4
Aramid B		1	12.7	12						
and	H1				3.40	2.7	3.60	5.1	3.80	9.0
high-strength polypropylene		1	12.7	38						

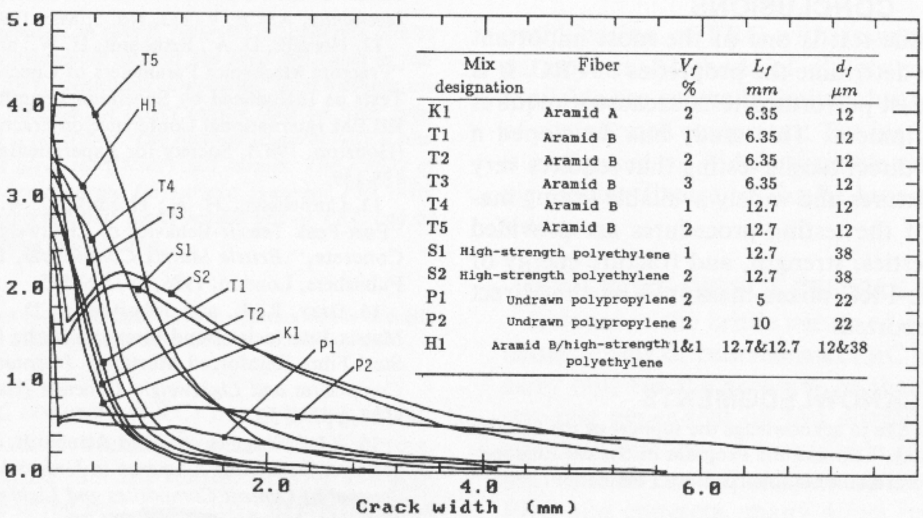


Fig. 8 — Stress versus crack separation curves for FRC

were prepared and tested, and at least five tests were completed without unexpected specimen failure. For each test, the maximum stress was calculated from the maximum load divided by the area of the specimen cross section, and the fracture energy was computed by numerical integration of the total area under the stress-crack opening curve. These results, together with the splitting tensile strength, are given in Table 1. Average σ-δ curves for these FRC mixes are shown in Fig. 8.

Table 1 illustrates that the tensile strength measured by the direct tensile tests is generally consistent with that by the splitting tensile test. With the reinforcement consisting of 1 to 2 percent low modulus undrawn polypropylene fibers (Mixes P1 and P2), the specimen strength is expected to be very close to that of plain mortar. The splitting tensile strengths of Mixes P1 and P2 were found to be somewhat higher than that of plain mortar, but the differences were within the normal range of strength variation between batches.

Depending on the fiber length and the volume fraction, the strengths of the aramid FRCs (Mixes K1 and T1-T5) are about 40 to 90 percent higher than that of FRC with undrawn polypropylene fibers. Fractographic observation revealed that most fibers in aramid FRC formed local bundles and that the matrix crack was deflected around or along these fiber bundles, resulting in a strength increase. However, the stresses decrease rapidly with an increase in crack opening, as indicated in Fig. 8.

For the high-strength polyethylene FRCs (Mixes S1 and S2), the strength does not significantly differ from that of FRC with undrawn polypropylene fibers. However, its post-peak stress decreases with crack opening less rapidly in comparison with aramid FRC. Significant amounts of high-strength polyethylene fibers in these composites were observed to be uniformly distributed in the matrix. Here the major mechanism contributing to the postcracking resistance was fiber pull-out. As a result, the fracture energy of high-strength polyethylene FRC is higher than that of most of the aramid FRC mixes.

The results seem to indicate that higher fracture energy is associated with longer fiber length. When two types of fibers (aramid and high-strength polyethylene) are used together as reinforcement, the performance of the hybrid FRC (Mix H1) is superior to FRC using only one of these fibers (Mix S1 or T4), and has relatively high strength and fracture energy.

Note that even for FRC mixes exhibiting relatively low fracture energies, these energy absorptions are still much higher than that of plain mortar, typically 0.01 kJ/m^2, and that of concrete containing coarse aggregates, typically 0.1 kJ/m^2.

Further discussions of the test results and fracture mechanisms observed in these tests can be found elsewhere.*

CONCLUSIONS

The direct tensile test is one of the most important measurements to determine the properties of FRC. It is also one of the least performed tests because it requires complicated equipment. This study has developed a novel method of direct tensile testing that requires very simple loading fixtures and widely available testing machines. Details of the testing procedures are provided and tensile properties, strength, and fracture energy of various synthetic FRC mixes measured by this direct tensile test are reported.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Shimizu Construction Company, Ltd. and the Program of System Engineering for Large Structures at the National Science Foundation.

CONVERSION FACTORS

1 mm = 0.03937 in.
1 N = 0.2248 lbf
1 MPa = 145.03 psi
1 kJ/m^2 = 5.7103 lbf/in.

REFERENCES

1. Hillerborg, Arne, "Analysis of Fracture by Means of the Fictitious Crack Model, Particularly for Fiber Reinforced Concrete," *International Journal of Cement Composites* (Harlow), V. 2, No. 4, Nov. 1980, pp. 177-184.

2. Li, Victor C., and Liang, Erwin, "Fracture Processes in Concrete and Fiber Reinforced Cementitious Composites," *Journal of Engineering Mechanics*, ASCE, V. 112, No. 6, June 1986, pp. 566-586.

3. Hillerborg, A., "Analysis of One Single Crack," *Fracture Mechanics of Concrete*, Elsevier Science Publishers, Amsterdam, 1983, pp. 223-249.

4. Evans, R. H., and Marathe, M. S., "Microcracking and Stress-Strain Curves for Concrete in Tension," *Materials and Structures, Research and Testing* (RILEM, Paris), V. 1, No. 1, Jan.-Feb. 1968, pp. 61-64.

5. Hughes, B. P., and Fattuhi, N. I., "Fiber Reinforced Concrete in Direct Tension," *Fiber Reinforced Materials*, Institution of Civil Engineers, London, 1977, pp. 141-147.

6. Hughes, Barry P., "Experimental Test Results for Flexure and Direct Tension of Fiber Cement Composites," *International Journal of Cement Composites and Lightweight Concrete* (Harlow), V. 3, No. 1, Feb. 1981, pp. 13-18.

7. Johnston, C. D., and Gray, R. J., "Uniaxial Tensile Testing of Steel Fiber Reinforced Cementitious Composites," *Testing and Test Methods of Fiber Cement Composites* (RILEM Symposium 1978), Construction Press, Lancaster, 1978, pp. 451-461.

8. Petersson, Per-Erik, "Crack Growth and Development of Fracture Zone in Plain Concrete and Similar Materials," *Report* No. TVBM-1006, Division of Building Materials, Lund Institute of Technology, 1981, 174 pp.

9. Morris, A. D., and Garrett, G. G., "A Comparative Study of the Static and Fatigue Behaviour of Plain and Steel Fibre Reinforced Mortar in Compression and Direct Tension," *International Journal of Cement Composites and Lightweight Concrete* (Harlow), V. 3, No. 2, May 1981, pp. 73-91.

10. Ohigashi, T., "Fracture Energy of Glass Fiber Reinforced Cement Composites: Method of Determination," *Cement and Concrete Research*, V. 14, No. 3, Mar. 1984, pp. 349-359.

11. Gopalaratnam, Vellore S., and Shah, Surendra P., "Tensile Failure of Steel Fiber Reinforced Concrete," *Journal of Engineering Mechanics*, ASCE, V. 113, No. 5, May 1987, pp. 635-652.

12. Hordijk, D. A.; Reinhardt, H. W.; and Cornelissen, H. A. W., "Fracture Mechanics Parameters of Concrete from Uniaxial Tensile Tests as Influenced by Specimen Lengths," *Proceedings*, SEM/RILEM International Conference on Fracture of Concrete and Rock (Houston, 1987), Society for Experimental Mechanics, Bethel, pp. 138-149.

13. Cornelissen, H. A.; Hordijk, D. A.; and Reinhardt, H. W., "Post-Peak Tensile Behavior of Lightweight versus Normal-Weight Concrete," *Brittle Matrix Composites*, Elsevier Applied Science Publishers, London, 1986, pp. 509-525.

14. Gray, R. J., and Johnston, C. D., "The Influence of Fibre-Matrix Interfacial Bond Strength on the Mechanical Properties of Steel Fibre Reinforced Mortars," *International Journal of Cement Composites and Lightweight Concrete* (Harlow), V. 9, No. 1, Feb. 1987, pp. 43-55.

15. Körmeling, H. A., and Reinhardt, H. W., "Strain Rate Effects on Steel Fibre Concrete in Uniaxial Tension," *International Journal of Cement Composites and Lightweight Concrete* (Harlow), V. 9, No. 4, Nov. 1987, pp. 197-204.

16. Li, V. C., "Fracture Resistance Parameters for Cementitious Materials and their Experimental Determination," *Application of Fracture Mechanics to Cementitious Composites*, Martinus Nijhoff Publishers, Dordrecht, 1985, pp. 431-449.

17. Ward, R. J.; Yamanobe, K.; Li, V. C.; and Backer, S., "Fracture Resistance of Acrylic Fiber Reinforced Mortar in Shear and Flexure," *Fracture Mechanics: Application to Concrete*, SP-118, American Concrete Institute, Detroit, 1989, pp. 17-68.

18. Li, Victor C., Chan, Chun-Man; and Leung, Christopher K. Y., "Experimental Determination of the Tension-Softening Relations for Cementitious Composites," *Cement and Concrete Research*, V. 17, No. 3, Mar. 1987, pp. 441-452.

19. Leung, C. K. Y., and Li, V. C., "Determination of Fracture Toughness Parameter of Quasi-Brittle Materials with Laboratory-Size Specimens," *Journal of Materials Science* (London), V. 24, 1988, pp. 854-862.

20. Li, V. C., and Ward, R. J., "A Novel Testing Technique for Post-Peak Tensile Behavior of Cementitious Materials," *Proceedings*, International Workshop on Fracture Toughness and Fracture Energy—Test Methods for Concrete and Rock (Sendai, 1988), A. A. Balkema Publishers.

21. Wang, Y., "Mechanics of Fiber Reinforced Cementitious Composites," PhD thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, June 1989.

22. Wang, Y.; Li, V. C.; and Backer, S., "Tensile Properties of Synthetic Fiber Reinforced Mortar," *International Journal of Cement Composites and Lightweight Concrete* (Harlow), V. 12, No. 1, Feb. 1990, pp. 29-40.

*Wang, Y.; Li, V. C.; and Backer, S., "Tensile Failure Mechanisms in Synthetic Fiber Reinforced Mortar," *Journal of Materials Science*, (London), forthcoming.

Authorized reprint from: September/October 1990 issue of ACI Materials Journal