Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

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Version of record first published: 02 Apr 2012.

Adv. Composite Mater., Vol. 10, No. 2,3, pp. 177–187 (2001)

Mechanical characterization of unidirectional CFRP thin strip and CFRP cables under quasi-static and dynamic tension

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Abstract—Under uniaxial tension, full stress–strain curves up to fracture and mechanical properties of a variety of CFRP cables having different structures are evaluated experimentally at three strain rates ranging from quasi-static (10^{-5} s^{-1}) to dynamic (10^{2} s^{-1}). Such properties as tensile strength, chord or tangent modulus, strain at tensile strength and absorbed energy per unit volume are obtained. Experimental difficulties on stress and strain measurements and specimen fastening are overcome by introducing special instrumental arrangements and an expansive-cement fastening technique. For all cables, at quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) strain rates, the stress–strain relation is linear. On the other hand, at a dynamic (10^{2} s^{-1}) strain rate, the stress–strain relation is non-linear and all cables tend to increase their elastic modulus and tensile strength. This obviously leads to increase of the absorbed energy per unit volume under dynamic tension. However, the strain at tensile strength remains almost the same at all strain rates. Thus, from a consideration based on the fracture strain criterion, it is concluded that strain rate insensitivity is assured for all cables.

Keywords: UD; CFRP cable; mechanical properties; dynamic tension; fastening; helix angle; infrastructure.

1. INTRODUCTION

Extensive research on advanced composite materials has already suggested that CFRP materials may be substituted for conventional steel for structure-reinforcing applications because of their high tensile modulus and tensile strength comparable with or higher than those of steel. Other performances of the material such as light weight, non-magnetic, non-corrosive, low linear thermal expansion and high fatigue resistance have focused engineers' attention on utilizing the material for the tensile element for applications in civil engineering and bridge construction, not only on the steel substitution basis but also with positive concepts of extending those material advantages [1]. Furthermore, the recent improvement of manufacturing technology and cost saving efforts for CFRP cables encouraged the research and project in this field. At the present time, CFRP cables are being recognized as a potential reinforcing element for infrastructure applications, for example, concrete beam reinforcement, bridge stay cables, ground anchor tendon, etc. [2, 3].

The strand structure of the CFRP cables in this study is similar to that of traditional steel cable or synthetic fiber rope in which wires or strings are gathered and twisted into spiral shapes. The number of pieces of wire, and the helix angle of spiral wire are important factors determining the structural performance of the cables. Effects of these factors on the tensile behavior at quasi-static strain rate (10^{-5} s^{-1}) of the CFRP cables was analyzed [4]; it was found that the number of pieces of string in CFRP cables itself did not apparently affect their tensile properties, while increasing helix angle above about 10 degrees degraded tensile properties except elongation at break. Our next step, therefore, is to conduct tensile tests at much higher strain rate levels, say 10^2 s^{-1}, at which infrastructures come to be forced as seismic impacts [5]. Strain rate effect on tensile properties of unidirectional (UD) CFRP examined here can also be compared with those of the other composite materials, AFRP and GFRP, which have been already given by the present authors [6, 7].

2. EXPERIMENTAL

2.1. Specimens

All specimens are fabricated from the same specified raw material CF prepreg: epoxy resin impregnated to unidirectionally arrayed carbon fibers (Besfight HTA 12K-P112, Toho Rayon). UD is prepared simply by curing the prepreg as received. Its fiber volume fraction is 57% and its cross-section is rectangular having typical dimensions shown in Table 1. Figure 1 shows some details of the CFRP cables fabricated. The symbol 1 is for a cable of only one string in which the prepreg is twisted in right-hand lay, or the so-called Z lay, with 23 mm pitch and is wrapped closely with polyester yarn. The symbols 1×2, 1×3 and 1×7 are for cables in which 2, 3 and 7 pieces of the above-mentioned string are twisted into strand structures with left-hand lay, or the so-called S lay, respectively. Thus CFRP cables are prepared by the process consisting of laying, wrapping, stranding and final curing at 130°C. The helix angle α as shown in Fig. 1, i.e. the angle between the spiral string and the axis of the cable, is 9.7 degree typically in 1×2, 1×3 and 1×7. Smaller and larger angles of 5.0 and 18.7 degree are also prepared for the 1×7 structure. Hence specimens of various structures (UD, 1, 1×2, 1×3 and 1×7) are used, and some have different helix angles (5.0, 9.7 and 18.7 degree for only 1×7 structure) as shown in Table 1. The outer diameter of CFRP string is 1.3 mm and the thickness of wrapped coating is about 0.15 mm. The diameter of CFRP part in a

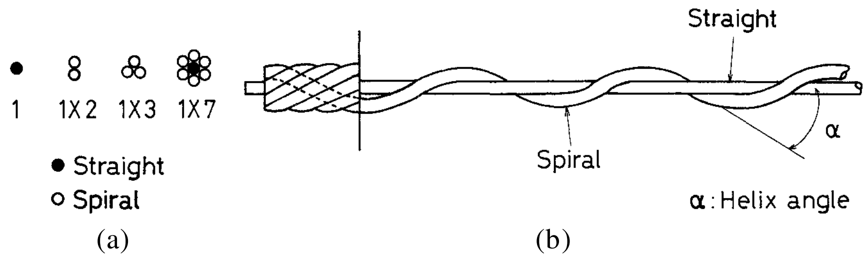


Figure 1. String array and helix angle of CFRP cables.

Table 1.
Variation of structure and helix angle of the specimens

Symbol	Number of pieces of string		Characteristic	Helix angle	Cross-sectional
	straight[a]	spiral	dimension(s)[b] (mm^2)	(deg)	area[c] (mm^2)
UD	1	—	2.3 × 0.4	—	0.810
1	1	0	1.3	—	0.724
1 × 2	0	2	2.6	9.7	1.47
1 × 3	0	3	2.8	9.7	2.20
1 × 7 S	1	6	3.9	5.0	5.08
1 × 7	1	6	3.9	9.7	5.13
1 × 7 L	1	6	3.9	18.7	5.31

[a] A string is not twisted for UD.
[b] Length of rectangular sides for UD. Diameter of a circumscribed circle for cables.
[c] Total area of CFRP parts in strings normal to the cable axis.

string is about 1.0 mm and its fiber fraction is 64%. The cross-sectional area of the cables is defined as the projected cross sectional area of CFRP part normal to the cable axis [4].

2.2. *Specimen fastening*

Generally, full stress–strain curves up to fracture for CFRP and other advanced composite materials are relatively difficult to obtain with conventional chucking techniques, such as screw threads, friction by transverse compression, adhesion and wedges. Thus, the present authors introduce a new fastening technique. The ends of the specimen are each inserted into a loose steel socket hole, and the loose gap between the specimen end and socket is filled with expansive cement. Uniform transverse compressive loading to the specimen over the socket hole length is applied by the expansion of the cement; this prevents the specimen from pulling-out of the sockets [8]. In the present case, this technique is the most suitable chucking technique and used for all specimens. However, a conventional fastening system in which specimen ends are embedded in epoxy resin and fixed by adhesion is still effective only at quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) strain rate tests. This is used partially in this study for 1, 1 × 2, 1 × 3 and 1 × 7 at these two strain rates. As shown in Fig. 2, cables were cut into pieces of 310 mm or 230 mm in length, where 80 mm of both ends were terminated with the filled socket system;

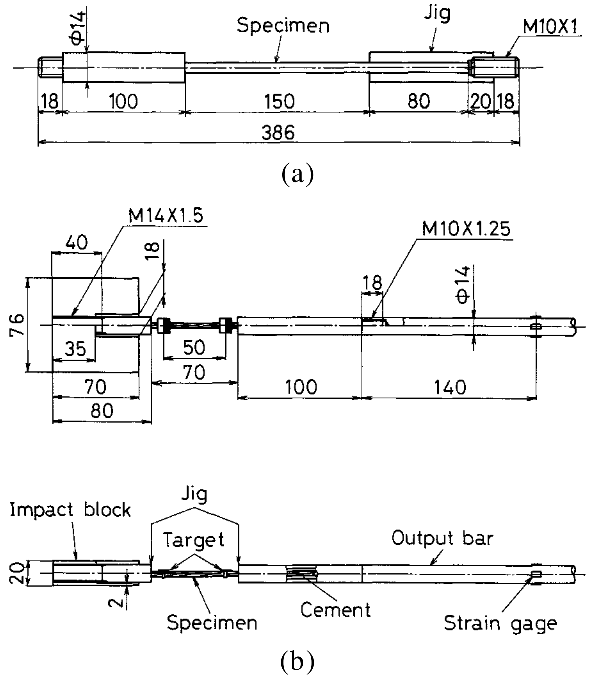


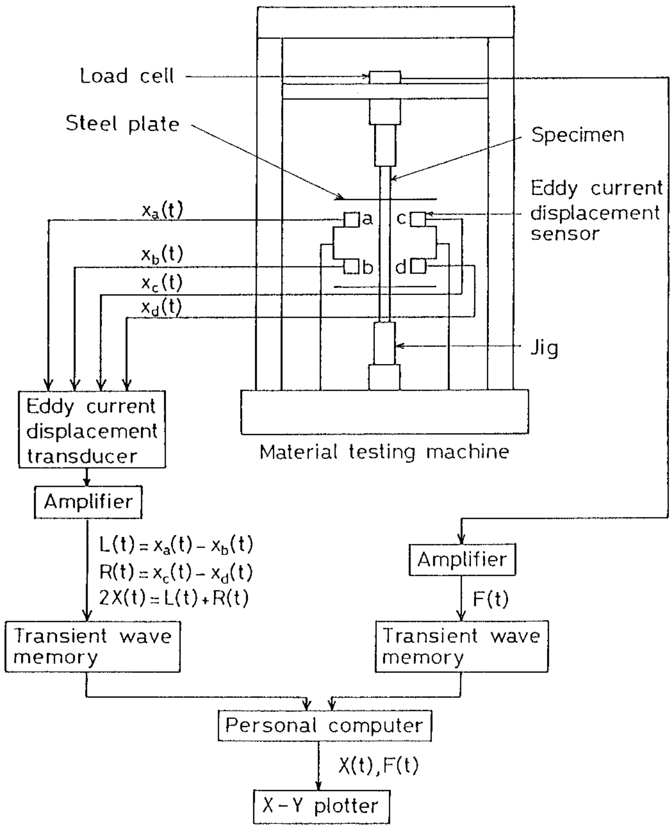
Figure 2. Assembled specimen for (a) 10^{-5} s^{-1} and 10^{-2} s^{-1} and (b) 10^{2} s^{-1} tensile test.

thus their effective length was either 150 mm or 70 mm. Curing conditions of the filling material were 20°C for 48 h and 120°C for 4 h for the expansive cement and epoxy resin, respectively.

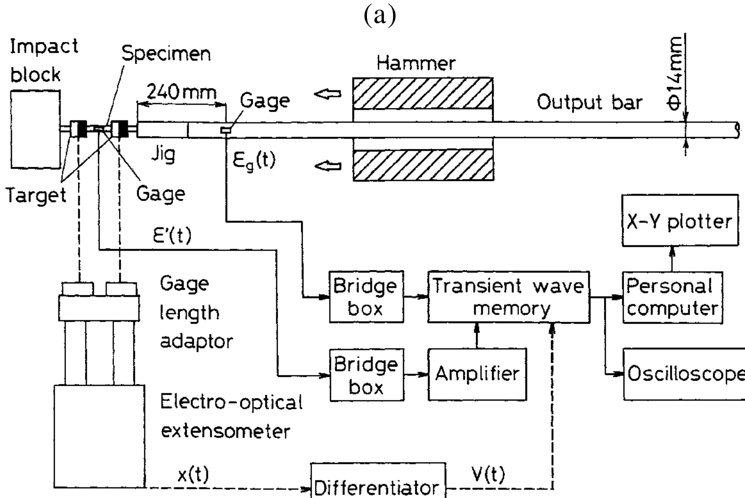
2.3. Experimetal procedures

For quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) tension, a special extensometer consisting of four eddy-current displacement transducers was devised, allowing initial geometric irregularities of a high-aspect-ratio specimen. The transducer detects the displacement of a target steel plate of 1 mm thickness which is clipped on the specimen with V-shaped attachment. The displacements of the upper and lower target plates are monitored by the transducers at two locations, i.e. the left and right sides and at the same horizontal distances of 30 mm from the specimen. Signals from two sensors for each plate are averaged so that any tilt of the target plate is cancelled around the cable axis at the attachment. The gage length is typically 88 mm. As shown in Fig. 3a, the extensometer is instrumented on a 98 kN universal material testing machine (Shimadzu AG-10TA). Crosshead speeds of 0.5 mm/min and 100 mm/min are used for quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) tensile tests, respectively.

On the other hand, under dynamic tension (10^{2} s^{-1}), a two-target version of the one-bar method gives rational stress–strain relations for even CFRP thin twisted structures. As shown in Fig. 3b, the two-target version of the one-bar method



(a)



(b)

Figure 3. Stress–strain measuring system for CFRP cables at the strain rates of (a) 10^{-5} s^{-1}, 10^{-2} s^{-1} and (b) 10^2 s^{-1}.

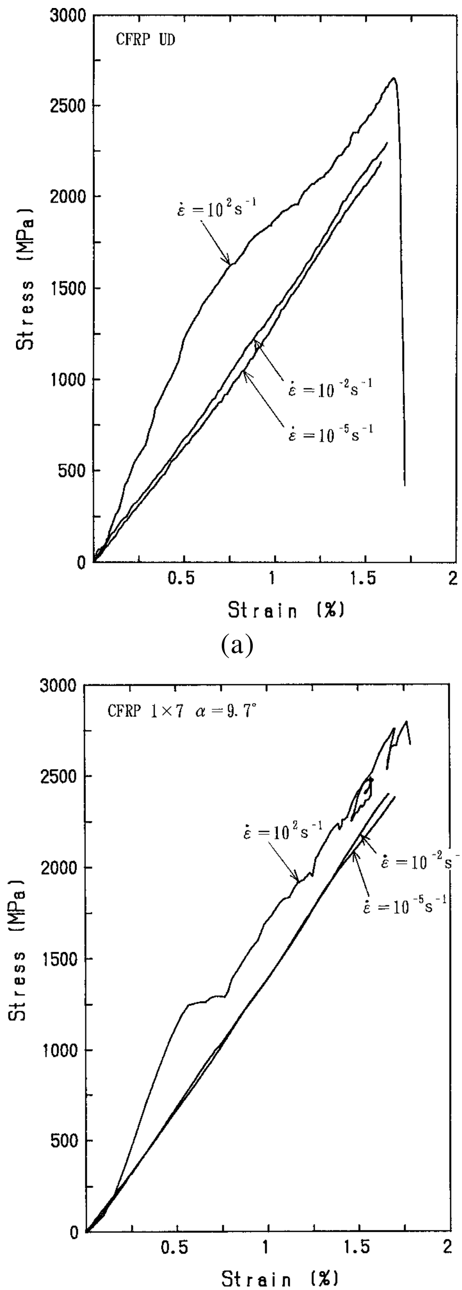
consists of a high-velocity loading machine and dynamic stress–strain measuring system. In this effective experimental method, in order to cancel the apparent strain induced by the end breakage of the fastening cement, two targets are adhered on the specimen itself to detect accurate elongation. Displacements of the targets are detected with an electro-optical extensometer (Zimmer model 200X, gage length of an installed lens: 5 mm). To verify the accuracy of the dynamic strain detection, the two-target method and a conventional strain gage method are tried simultaneously, as a preliminary experiment. In the former method, two black-and-white paper targets backed by a square aluminum sheet are adhered on the specimen of 50 mm gage length, by small spots of epoxy adhesive. In the latter method, a strain gage (Kyowa KFG-02-120-C1-11, gage length: 0.2 mm) is cemented directly on the specimen. However, its surface roughness is not perfectly good as a gage station. Prior to the cementing, epoxy resin is applied on the specimen as thinly as possible, as a gage station base. A slingshot loading system is able to give a hammer velocity of 10 m/s typically. The dynamic loading to the specimen is applied via an impingement between the hammer and impact block. The signals from both methods are stored by three synchronized digital memories (Kawasaki Electronica TMR-100, resolution: 10 bits, sampling frequency: 1 MHz). After the rupture of the specimen, load and displacement data are reduced to stress and strain values via a personal computer. The agreement between the two strain detection methods is fairly good. After that, only the one-bar method is used in this series of experiments.

3. RESULTS AND DISCUSSION

3.1. Stress–strain relations

Typical stress–strain curves of UD are shown in Fig. 4a. At both quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) strain rates, stress–strain curves are linear, and the difference between them is quite small. On the other hand, at dynamic (10^{2} s^{-1}) strain rate, the stress–strain curve is no longer linear. The curve shows an increase in elastic modulus initially, which is followed by a gradual decrease until strain reaches 1.3%. Then at a strain close to the specimen breakage, elastic modulus lowers to almost the same level as that in quasi-static tension. Thus the stress–strain recording draws a convex curve in dynamic tension. The behavior for 1×7 at three strain rates, as shown in Fig. 4b, is almost similar to that of UD. However, the enhancement of elastic modulus in dynamic tension is smaller than that of UD, since the increase of elastic modulus at the initial part is followed by a drop from 0.5% to 0.75% strain.

Furthermore, at a region close to the specimen breakage, an irregular 'loop formation' on the stress–strain curve is sometimes observed in dynamic tension. The reason for this is not understood, while some possibilities are considered such as a local failure in individual strings of 1×7, a collapse of array of strand and a



(a)

(b)

Figure 4. Stress–strain curves of (a) CFRP UD and (b) CFRP 1 × 7 at three strain rates, 10^{-5} s^{-1}, 10^{-2} s^{-1} and 10^2 s^{-1}.

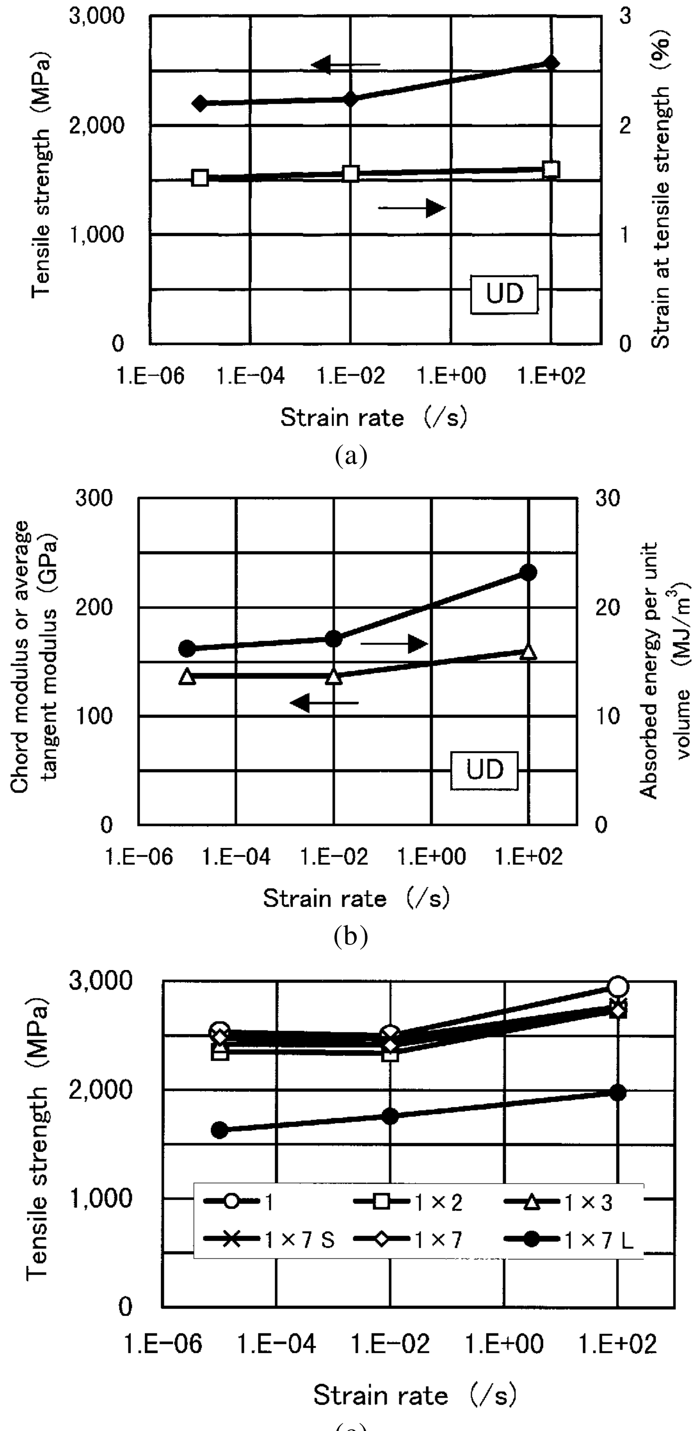
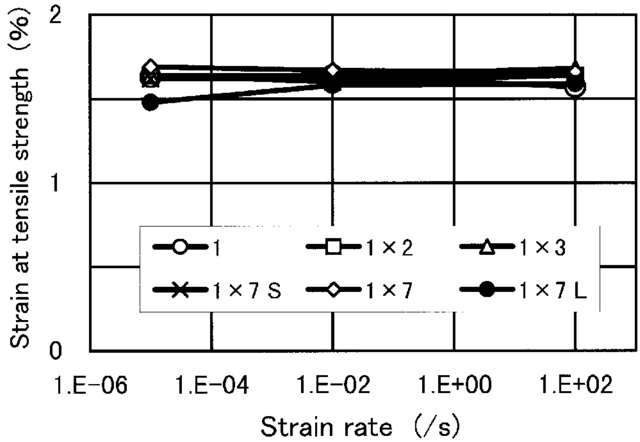
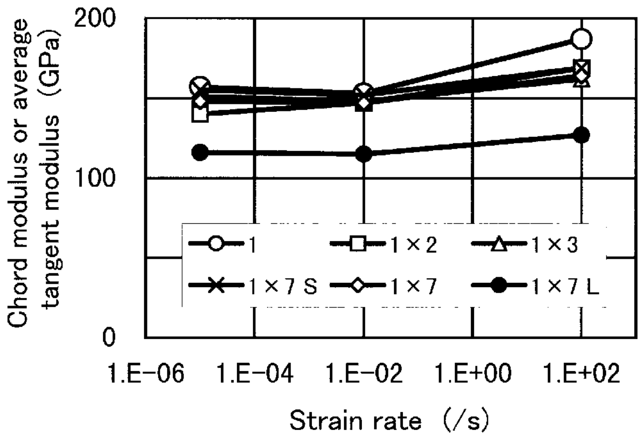


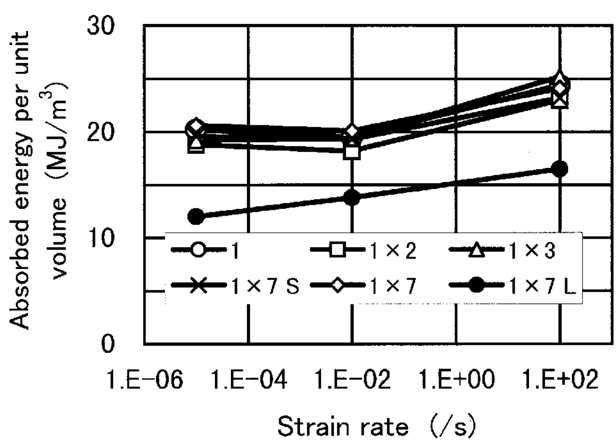
Figure 5. Strain rate effect in tensile characteristics of CFRP UD and CFRP cables.



(d)



(e)



(f)

Figure 5. (Continued).

very small scale pull-out from fastened part. All of them can cause an instantaneous relaxation of tension, but this is not a fatal problem.

3.2. Strain rate dependence of tensile properties

From the stress–strain curves obtained, the tensile strength, strain at tensile strength, elastic (chord or tangent) modulus and absorbed energy per unit volume are evaluated. At quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) strain rates, since the stress–strain relation is linear, the chord modulus is calculated from the stresses at the strains of 0.2% and 1.0%. On the other hand, at dynamic (10^{2} s^{-1}) strain rate, the stress–strain behavior is not linear as described in the preceding section, and the tangent modulus is adopted as a measure of elastic property. Average tangent modulus here is calculated as a mean value of slopes of the upward part of dynamic curve, using the Savitzky–Golay method based upon the least square procedure. The absorbed energy per unit volume is obtained from the area of the stress–strain curve. Tensile properties *vs.* strain rate for UD and CFRP cables are shown in Fig. 5. Mean values of 4 or 5 data are plotted.

Tensile properties remain almost the same for UD and CFRP cables in quasi-static and intermediate tension. However, except the strain at tensile strength, increases in tensile strength, elastic modulus (chord or average tangent modulus) and absorbed energy per unit volume with increasing strain rate from intermediate to dynamic tension, are observed for all CFRPs. The elastic modulus enhanced at dynamic tension increases the tensile strength and absorbed energy per unit volume. From the fracture strain criterion, it is found that the whole CFRP cable is strain rate insensitive, since strain at tensile strength is almost constant over the strain rate region tested. This insensitivity is similar to that of AFRP UD [6, 7].

4. CONCLUSIONS

The following is concluded in the present mechanical characterization of CFRP UD and CFRP cables over a wide strain rate range (10^{-5}–10^{2} s^{-1}).

1. The specimen fastening technique using expansive cement works well to fasten CFRP UD and CFRP cables, especially in dynamic tension.
2. Stress–strain relation is linear at quasi-static (10^{-5} s^{-1}) and intermediate (10^{-2} s^{-1}) rates of strain in tension for CFRP UD and CFRP cables. No obvious change in their mechanical properties is observed at these strain rates.
3. In dynamic tension (10^{2} s^{-1}), tensile response enhances tensile modulus and the stress–strain relation becomes non-linear. But strain at tensile strength remains almost constant. Accordingly, this increases tensile strength and absorbed energy per unit volume.
4. CFRP UD and CFRP cables show strain rate insensitivity from 10^{-5} s^{-1} to 10^{2} s^{-1}. This property is similar to that of AFRP UD.

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