Dynamic Tensile Properties of CFRP Cables subjected to High-speed Loads

Motoyama, Hiroyuki
Department of Aerospace Engineering : National Defense Academy : Yokosuka : Research Assistant

Ohta, Toshiaki
Department of Civil and Structural Engineering : Professor

Ono, Tomonori
Department of Civil Engineering : National Defense Academy : Yokosuka : Professor

Moriya, Kazumasa
Department of Aerospace Engineering : National Defense Academy : Yokosuka : Professor

https://hdl.handle.net/2324/1115

出版情報：九州大学工学紀要. 62 (3), pp.113-127, 2002-09-26. 九州大学大学院工学研究院

Memoirs of the Faculty of Engineering, Kyushu University, Vol. 62, No. 3, September 2002

Dynamic Tensile Properties of CFRP Cables subjected to High-speed Loads

by

Hiroyuki MOTOYAMA*, Toshiaki OHTA**, Tomonori OHNO***
and Kazumasa MORIYA****

(Received June 28, 2002)

Abstract

It has well known that Carbon Fiber Reinforced Plastic (CFRP) cables show their excellent performances in lightweight, high strength, no-magnetism and corrosion-resistance. And thus they are being expected to use as structural members in space structures or in civil engineering fields in place of steel ones. However, since CFRP cables have been currently very few applications available, their physical properties have not been still cleared. This study is to investigate fundamentally the dynamic tensile properties of CFRP cables. Dynamic tensile tests for CFRP cables were executed by making use of the hydraulic rapid loading machine, which has the maximum loading capacity of 980 kN and the maximum loading speed of 4 m/s. From test results, it can be found that the failure strength of CFRP cables becomes smaller with the increase of loading rates and the performances of carbon fibers at breakage for high-speed loads quite differ from that for static loads.

Keywords: CFRP cable, Dynamic tensile property, Rapid loading tensile test, High-speed load

*Research Assistant, Department of Aerospace Engineering, National Defense Academy, Yokosuka
**Professor, Department of Civil and Structural Engineering
***Professor, Department of Civil Engineering, National Defense Academy, Yokosuka
****Professor, Department of Aerospace Engineering, National Defense Academy, Yokosuka

1. Introduction

Carbon Fiber Reinforced Plastic (CFRP) cables have great industrial potential on account of their excellent performances in lightweight, high strength, no-magnetism and corrosion-resistance. Such space structures as a satellite loaded with an antenna and a solar battery array have been getting larger scale year by year according to the increase of mission demand. Considering the current and future situation, the deployable structures are the most common as a stowage of satellite for transportation to the orbit. In this deployable structure, many flexible metal or fiber cables are used to lighten and simplify the deployment mechanism without losing the functional accuracy and reliability of structure. In the field of aeronautical engineering, many studies[1,2] related on the steel cables have been steadily done to examine the mechanical properties of them. In recent years, the application of cable network, tension truss and space tether to deployable space structures have been studied[3-7]. Of these, the studies on CFRP cables are extremely few even though they are indispensable and important[8].

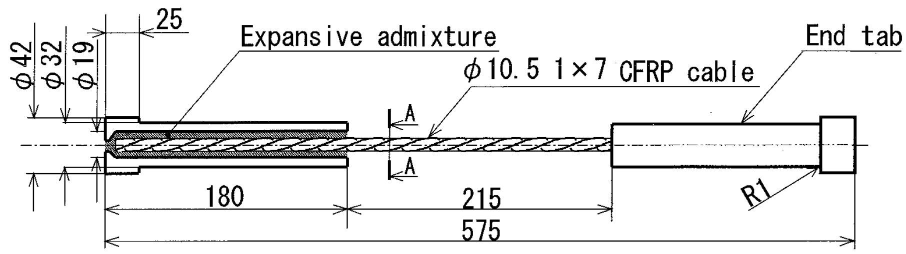
For the other fields, in civil engineering, CFRP cables and sheets have been practically used for many structures. For instance, Reinforced Concrete (RC) bridge piers, which they are to be suffered from salty breezes, were strengthened by CFRP cables in place of reinforcing steel bars[9]. Also, after the great Hanshin-Awaji Earthquake in 1995, the existing bridge piers have been retrofitted and reinforced by CFRP sheets[10,11], and many studies on the application of CFRP materials to structures have been continued[12-15]. However, most of these studies are related on the static physical properties of CFRP cables[16,17]. As of studies on the dynamic tensile properties[18,19] of them were resulted from impact tests by the weight-drop or the rotating circular plate impacting machines. In these tests, though the dynamic properties of CFRP cables under very high strain rates can be found, it may be affected by a high stress wave simultaneously. It is known that impact tests are commonly employed for investigating the behaviors of structural materials and members subjected to impact loads. Thus, to examine and find precisely the dynamic properties of structural materials without stress wave effects, a rapid loading test should be employed.

This study is to examine the tensile properties of CFRP cables with strain rate effects. Then different five loading rates were chosen as test parameters in the rapid loading tests. CFRP cable specimens for this test have the same specifications as ones used in the previous static tensile tests. In tests, specimens were tested until the tensile breaking will occur. Based on test results, the tensile failure load, the elongation at breakage and the energy absorption capacity were examined and related with the strain rates of 10^{-4} to 10^{1} (1/s).

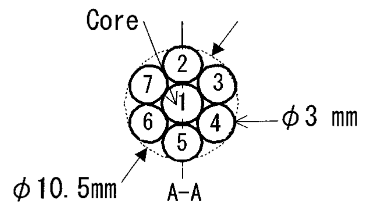
2. Outline of dynamic tensile tests for cable specimens

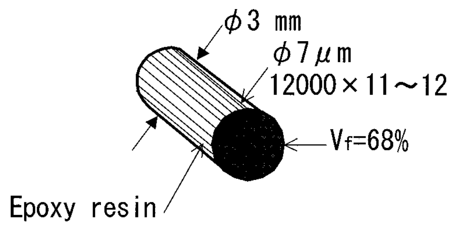
2.1 CFRP cable specimens

Fig.1 shows the configuration of CFRP cable specimen used for the dynamic tensile tests. A CFRP cable is made of seven strands, in which six strands were twisted spirally around a core strand as shown in **Fig.1(b)**. Each strand is bundled



(a) Geometry of specimen.





(b) Cross section of cable. (c) Strand.

Fig. 1 Specimen.

of 12000 Poly Acrylo Nitrile (PAN) series carbon fibers impregnated with epoxy resin, which has the 3 mm in diameter (manufactured by Tokyo Rope Co. Ltd.) as shown in **Fig.1(c)**. It was found from the photographic line method that CFRP cable has the fiber content of 68% by volume, the nominal diameter of 10.5 mm and spiral pitch of 130 mm. A specimen has 215 mm in gauge length and 575 mm in full length. Both ends of a cable were inserted into the tab, which is made of mild steel, with the outside diameter of 32 mm, the inside diameter of 19 mm and 180 mm in length. Then, both the end tabs were filled with the expansive admixture, which is commonly used to break rocks or RC structures in civil engineering fields. A specimen was installed in a correctional device to align and the expansive admixture was hardened under the room temperature. The compressive pressure by the expansive admixture becomes about 60 MPa in a week after fixation and continues to increase day by day. For this test, the specimens cured for two weeks were employed.

To measure the strain in a CFRP cable specimen, three strain gauges (FLA-5-23, 5 mm in length) were attached to the center position and other two positions of 20 mm from each tab (i.e., the interval of about 85 mm) in the direction of the spiraled side wire of a cable. In tests, three specimens were tested under the same testing condition.

2.2 Dynamic tensile testing procedures

The dynamic tensile tests were performed by making use of the rapid loading test machine (the loading capacity of 980 kN, the maximum loading speed of 4 m/s) as shown in **Figs.2** and **3**. Bearing force and displacement of a cable specimen and strains in the spiraled side wire were measured by the load transducer of 490 kN, the laser non-contact displacement sensor (the resolution of 50 μm and the capacity of 200 mm) and strain gauges, respectively, as illustrated in **Fig.4**. The measured data from measuring devices were recorded and analyzed by the data acquisition system (the maximum measuring frequency of 10 MHz). In measurement, the data sam-

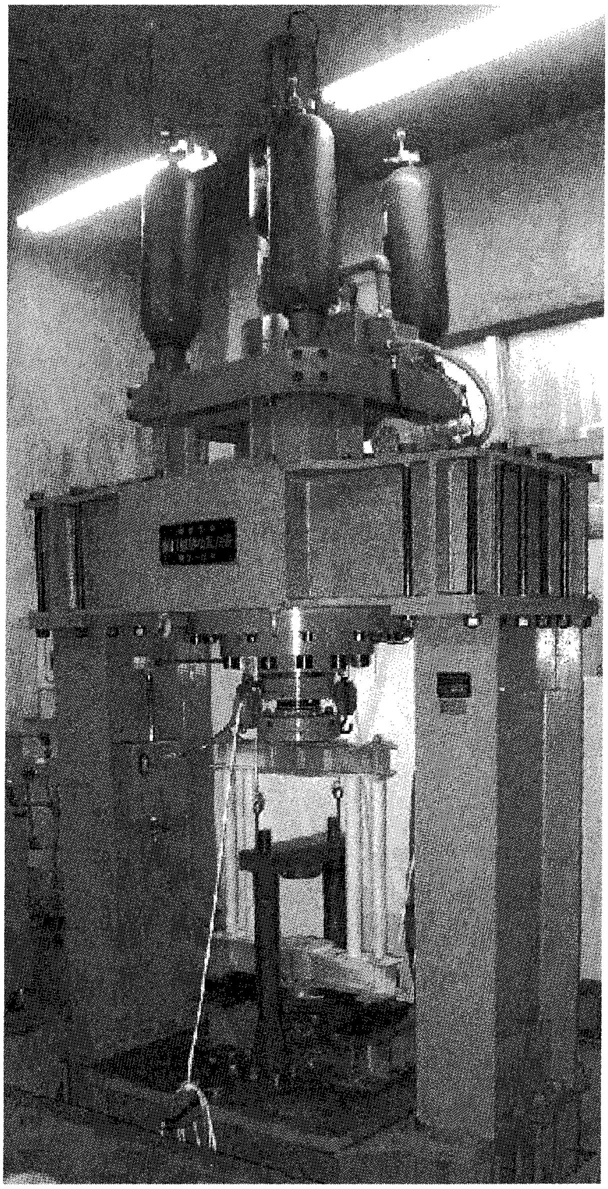


Fig. 2 Experimental instruments and rapid loading machine.

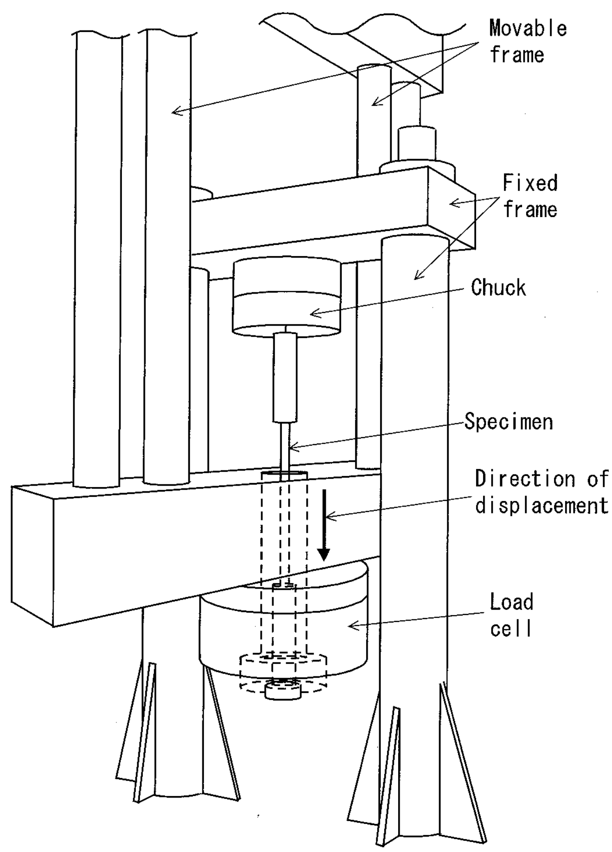


Fig. 3 Experimental setup.

pling frequencies were varied from 20 kHz to 1 MHz corresponded with the loading rates. And, the states of all tests were also recorded by the high-speed video camera (NAC HSV-400, 400 frames per second).

The rapid loading test machine is principally consisted of a main actuator, a balance actuator and a servomechanism actuator. Before starting a test, the main actuator is constrained by the balance actuator to work. And, a servomechanism actuator will work to open oil holes in the balance actuator, and then the main actuator starts loading. Loading speed is controlled by the operational speed of a servo-valve, that is, the opening speed of in-and-out holes in the oil cylinder will be operated. Tensile testing instrument is consisted of two steel rigid frames. These two frames are combined so as to make a right-angled crossing as shown in **Fig.3.** A load transducer and a specimen fixation device are equipped in a movable frame (four steel bars with the diameter of 50 mm and two of H-shaped beams) fixed to the main actuator. Other frame (two steel columns with a diameter of 90 mm and a steel beam with the size of 75 × 150 × 500 mm) is fixed to the reaction base of test machine as shown in **Fig.5.** Force to the specimen was loaded to the lower end of

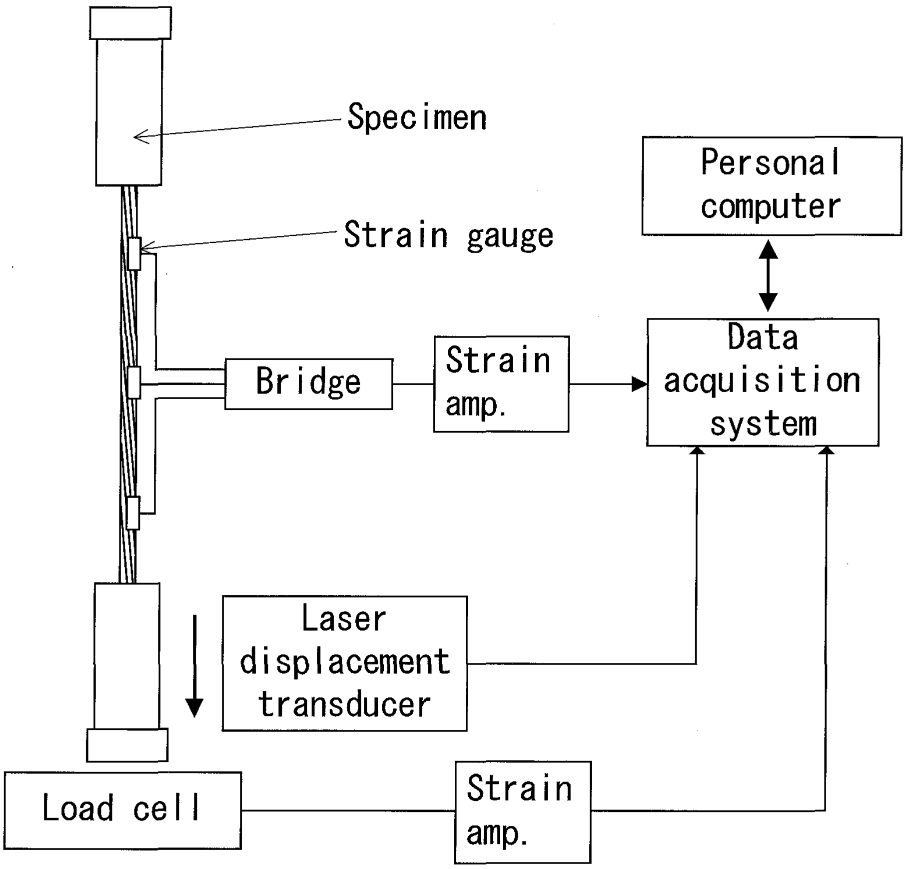


Fig. 4 Schematic diagram of measuring system.

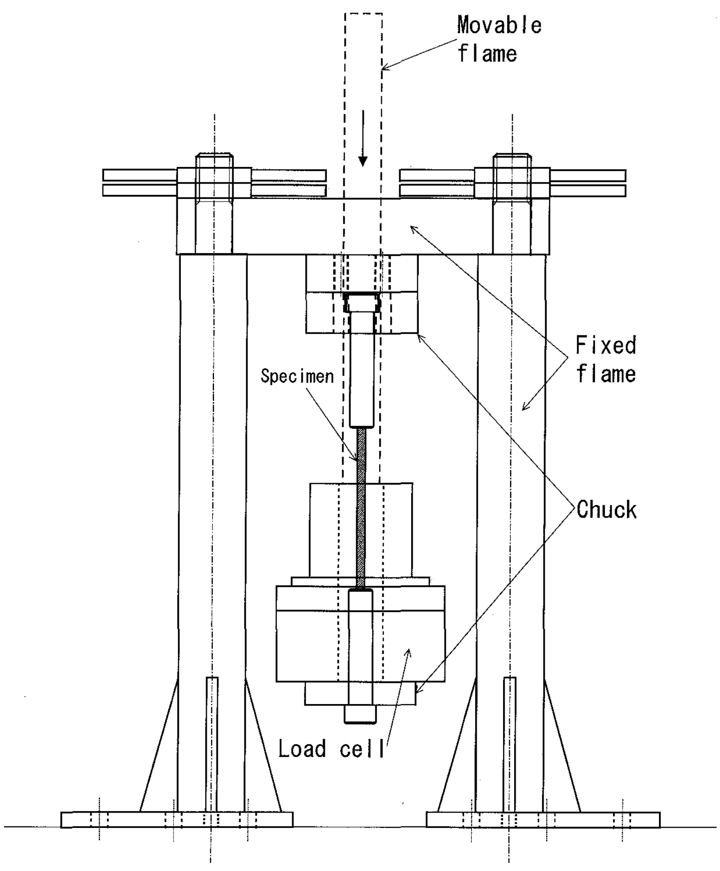


Fig. 5 Fixed flame.

specimen fixed to the movable frame as shown in **Figs.3** and **5**.

As given in **Table 1**, the loading rates were designated for five levels as very

Table 1 Testing conditions.

No.	Name	Displacement speed (m/s)	Anticipation Strain rate(1/s)	Number of specimens
1	Very low (VL)	1×10^{-4}	4.65×10^{-4}	2
2	Low (L)	0.10	0.47	3
3	Middle (M)	0.34	1.59	3
4	High (H)	1.17	5.44	4
5	Very high(VH)	4.00	18.60	5

low, low, middle, high and very high, which corresponds to the expected strain rates. In this study, the stress and the tensile strength can be evaluated by dividing the measured load by the nominal cross-section area. Here, since the strain was measured by the strain gauges attached to the spiraled wire of cable, this strain are not exactly the true axial strain in a cable.

3. Experimental results and considerations

3.1 Results from quasi-static tensile test

The relation between the load and the elongation of a CFRP cable specimen by quasi-static tensile tests is shown in **Fig.6**. Here, the elongation is given as the averaged value of the data from three strain gauges. The load and elongation-time histories are also shown in **Fig.7**. It can be found from **Fig.6** that the relation between the load and elongation is given as a straight line up to the failure (i.e., the breaking point) of cable. In this case, the averaged tensile failure load of two specimens was 114.5 kN and the averaged elongation at the breaking point was 1.35%. Although the elongation shown here is the strain in the direction of a spiraled side

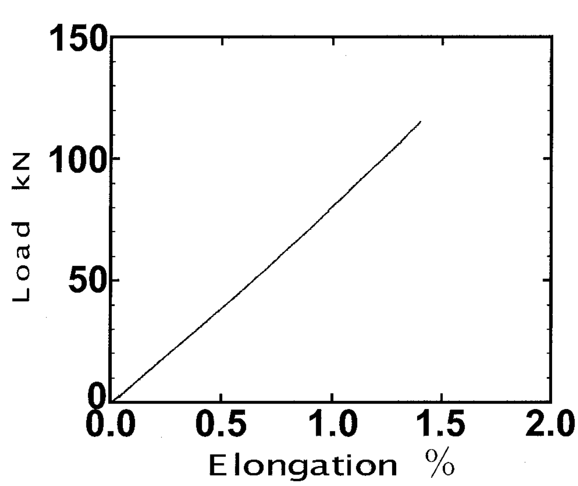


Fig. 6 Load vs. elongation at the quasi-static test.

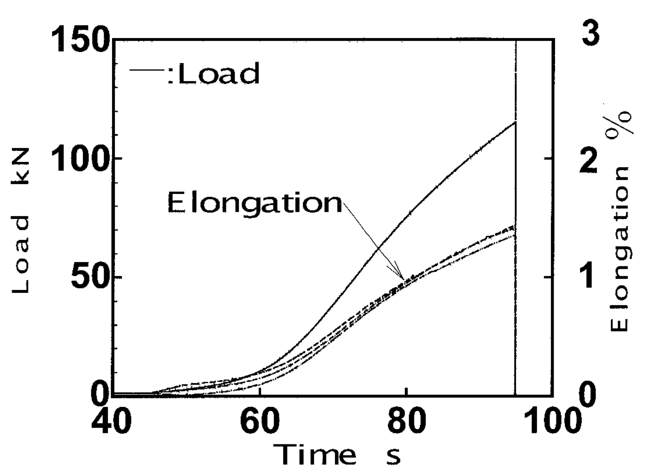


Fig. 7 Load and elongation vs. time at the quasi-static test.

wire, this agrees well with the experimental result obtained by measuring directly the directional elongation of cable specimens[17]. This may be an accidental result, but the elongation evaluated from the strain in spiraled wires can be acceptable as the directional elongation of a cable. Moreover, from results in the quasi-static tensile tests of CFRP cables, it is hard to find out the phenomenon[1, 20], which the tensile elastic modulus increases greatly in the early loading stage due to the frictional resistance between the side wires and the core wire and/or the uneven of twist in a steel wire cable. The averaged tensile elastic modulus determined from the linear relation of load and elongation in the early loading stage was 134 GPa. When a twisted strand is pulled under the condition of free rotation, a twist will be returned and a strand will rotate. Even though the fixing device of a cable specimen used for this test has the rotational mechanism, the rotation of a cable specimen was not observed until it is broken since the weight of fixing device is very large.

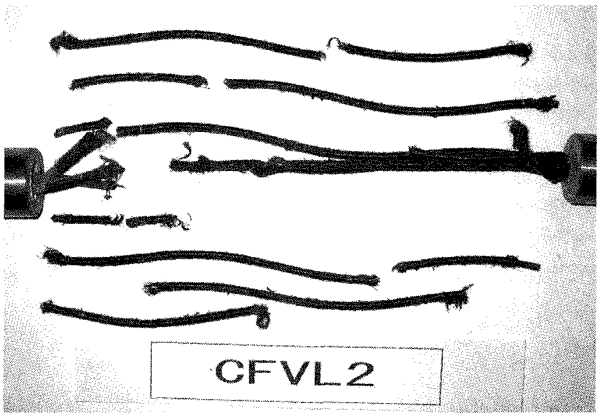


Fig. 8 Photograph of fractured cable at the quasi-static test.

An example of a fractured CFRP cable specimen by the quasi-static tensile test is shown in **Fig.8**. It can be seen from the figure that the fracture of a cable by the quasi-static tensile test will occur when all strands break simultaneously in pieces. To see how the fractured cross section was, the difference of applied stress states can be found. That is, when one side of fractured section becomes the serrated surface, the other section has the inclined and smoothed surface. This may be resulted that both the tensile and compressive failure were occurred and intermingled in the same strand. The breakage in a CFRP cable specimen will occur in the specified section at first by tensile stress, and then the internal energy may be released at this time. This will cause the compressive failure at the other section since a cable contracts abruptly so as to return to its original dimensions. However, since the failure in a cable occurs instantly, it is difficult to determine where the broken section was originated at first.

3.2 Results from high-speed tensile test

3.2.1 Failure state

The failure states of CFRP cable in the high-speed tensile tests are shown in **Figs.9-12**. In the high-speed tensile tests, CFRP cables were resulted to the failure

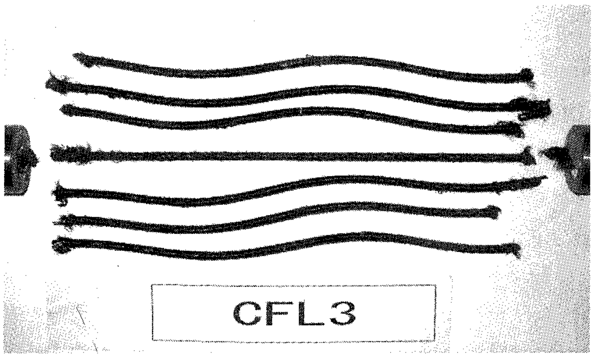


Fig. 9 Photograph of fractured cable at the high speed test (0.10 m/s).

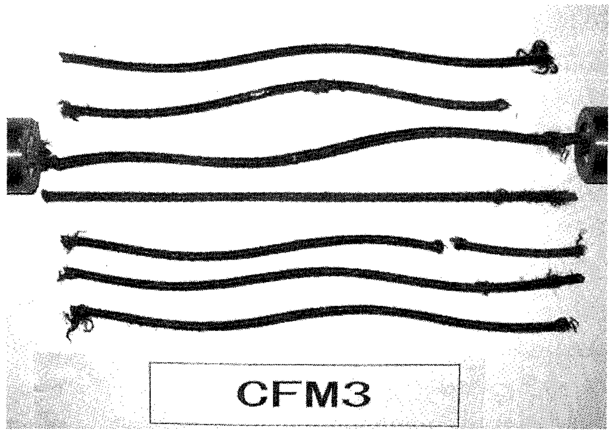


Fig. 10 Photograph of fractured cable at the high speed test (0.34 m/s).

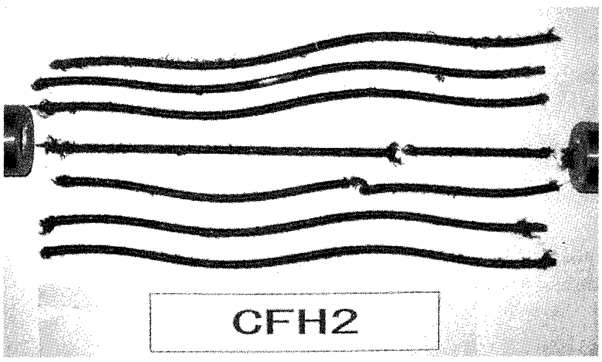


Fig. 11 Photograph of fractured cable at the high speed test (1.17 m/s).

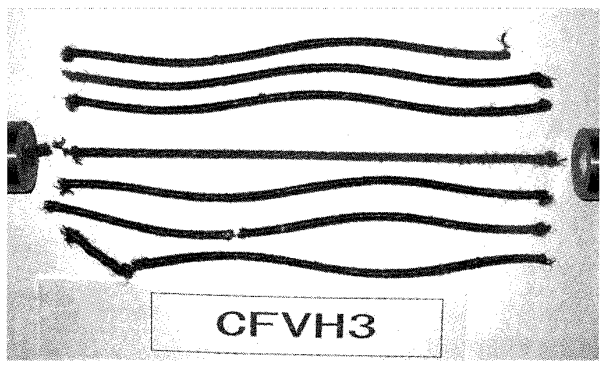


Fig. 12 Photograph of fractured cable at the high speed test (4.00 m/s).

when all strands broke simultaneously and instantly, which is similar to the case in the quasi-static tensile tests. Compared the failure states for high-speed loads with that for quasi-static tensile loads shown in **Fig.8**, it can be found that the broken positions of strands in the two are greatly different. For high-speed loads, in 13 of 15 specimens, all strands of a cable were broken at both ends near the tabs. While for quasi-static loads, all strands were broken in pieces over the length. As common knowledge in material tests, the breakage at near the fixed end may be resulted due to the stress concentration. And thus, it might be pointed out that the breakage at both ends was caused by a method of chucking specimen. It is thought from the experimental facts that, though there is no evidential correlation, the breakage of cable specimens at both ends may be in connection with that the failure load decreases with the increase of strain rates. Since the breakage at both ends of a cable is happened only in high-speed tensile loading tests, it may be concluded that this will due to the stress localization but the stress concentration. In quasi-static tensile tests, even if a tensile load is applied unequally to each strand due to the geometric gap or imbalance of a cable at the beginning, these defects will be gradually eliminated as time passed and deformation progressed. While, for high-speed tensile tests, since there is no time to recover the uniformity of a cable, the breakage will be localized in a certain part where the stress concentrates.

In this study, the fixing method of a cable specimen is referred to the common method, which is currently and generally employed for the tensile tests of cables. From test results in this study, when the dynamic tensile properties of cable specimens subjected to high-speed loads or impact loads will be examined further, the fixing method of a cable specimen in tests should be improved or newly developed.

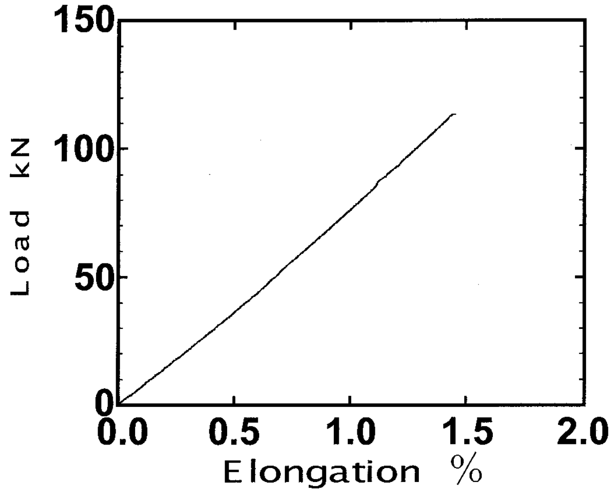


Fig. 13 Load vs. elongation (0.10 m/s).

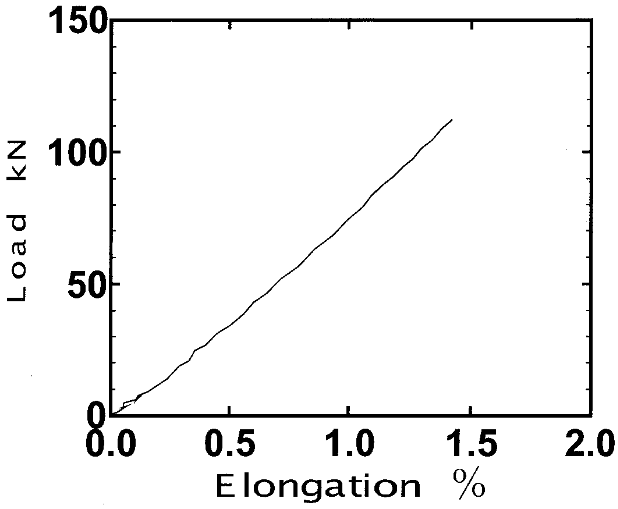


Fig. 14 Load vs. elongation (0.34 m/s).

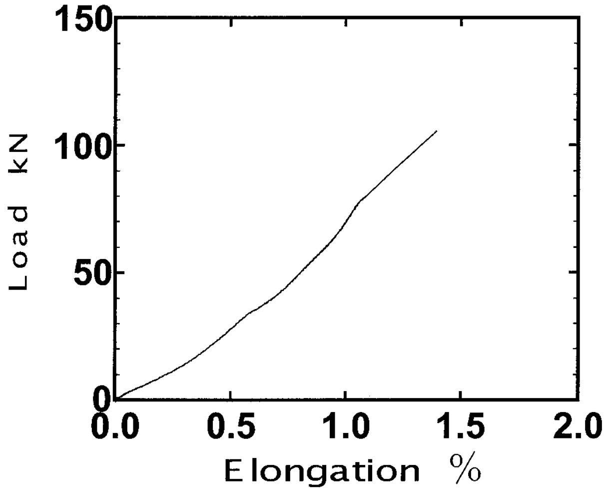


Fig. 15 Load vs. elongation (1.17 m/s).

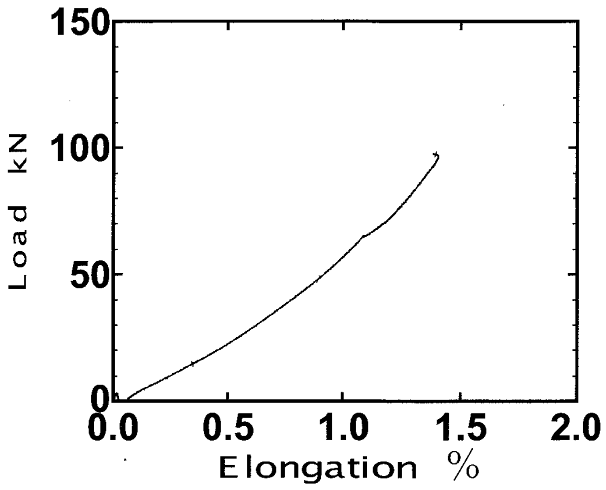


Fig. 16 Load vs. elongation (4.00 m/s).

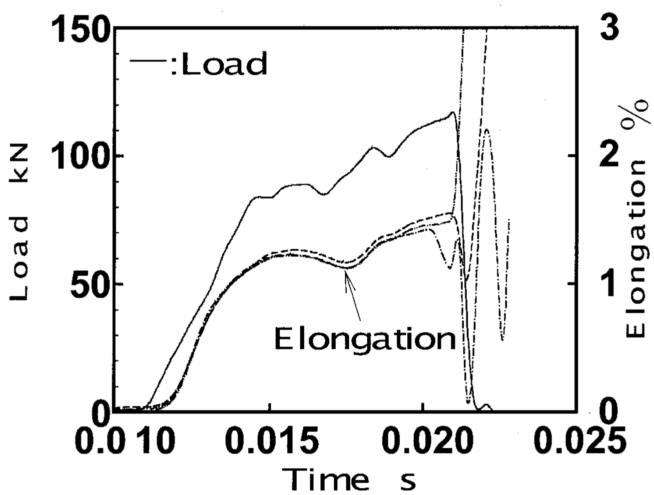


Fig. 17 Load and elongation vs. time (1.17 m/s).

As an example, the tip of a tab with a taper shape is proposed. As to the fractured surface in strands, the tensile-type fracture was observed in one end and the other end was the compressive-type fracture. It is concluded that the fracture mechanism for high-speed loads is quite similar to that for quasi-static loads.

3.2.2 Load and elongation relation

The relations between load and elongation of CFRP cable specimens resulted from high-speed tensile tests are shown in **Figs.13-16.** **Fig.17** shows a typical example of time histories of load and elongation, in the case of loading rate of 1.17 m/s. Here, the elongation is given by rating the measured strain. It can be found from **Figs.13-16** that the load-elongation relations are somewhat changed when the loading rate becomes larger. The load- elongation relations in the case of loading rates of 0.10 to 0.34 m/s are almost linear up to the breaking point in the same as that for the case of quasi-static loading. When the loading rate becomes larger than 1.17 m/s, the elongation of cable will be developed 0.5 ms behind the load, as shown in **Fig.17**, since a slight play may be possibly existed in the mechanical joints or other. Generally, in dynamic tests, the load data measured with a load transducer is strongly affected by the inertia when the loading speed becomes larger. Thus, the results shown in **Figs.15** and **16** are given after the effect of inertia force was removed. From these figures, the load-elongation relations for the case that the loading rates are over 1.17 m/s, it can be seen that they show a weak non-linearity. And, as can be seen from **Fig.17**, the differences among the strain at three points were not recognized in both time and value. Based on AE (Acoustic Emission) method, the stress wave velocity in a CFRP cable is about 8000-9000 m/s. This means that it takes 9 μs the stress wave to propagate between two strain gauges with the interval of 85 mm, and thus the difference of localized deformation can be neglected. At the moment when a cable is broken, the output from three strain gauges change with the location to either increase or decrease as shown in **Fig.17**. This may be considered that the compressive stress will be originated in a localized certain part in the same phenomena as that for quasi-static tensile tests.

3.2.3 Failure load

The relation between the failure load and the strain rates resulted from high-speed tensile tests is shown in **Fig.18**. In this study, the strain rate is defined as

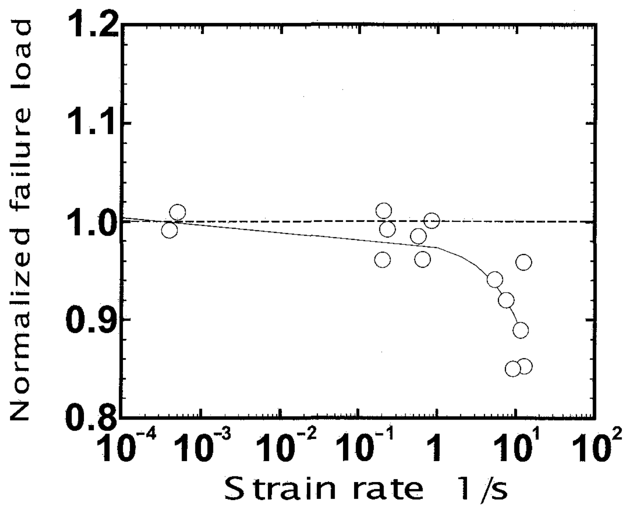


Fig. 18 Failure load vs. strain rate.

the slope of the tangent to the strain-time curve, in which the behaviors of three measured strains show almost same. And, the failure load shown in **Fig.18** is normalized with the averaged failure load obtained from static tensile tests. The failure loads of CFRP cables under the conditions of the strain rates of less than 1.0 (1/s) are nearly equal to that for the static tensile test. When the strain rate becomes larger than 1.0 (1/s), the failure load remarkably deteriorate. At the strain rate of about 10.0 (1/s), the failure load is about 10% lower than that for the static tensile test. Based on the results from the high-speed tensile test, the failure load of CFRP cable is related with the strain rates by

$$\frac{L_d}{L_s} = \left(\frac{\varepsilon_d}{\varepsilon_s}\right)^{-2.44\times10^{-3}} \times e^{(-3.61\times10^{-6})\times\left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)} \quad (1)$$

where L_d is the failure load (kN) for a high-speed tensile load, L_s is the averaged failure load (kN) for the static tensile test, $\dot{\varepsilon}_d$ is the strain rate (1/s) in a high-speed tensile loading, $\dot{\varepsilon}_s$ is the strain rate (1/s) in the static tensile test, e.g., $\dot{\varepsilon}_s = 10^{-4}$. The failure load-strain rate relation calculated from Eq.(1) is given in **Fig.18** by the thin line.

3.2.4 Ultimate elongation

The relation between the ultimate elongation and the strain rates for the high-speed tensile test is shown in **Fig.19**. The ultimate elongation of CFRP cable is defined as the elongation when the maximum load (or the failure load) is applied to a

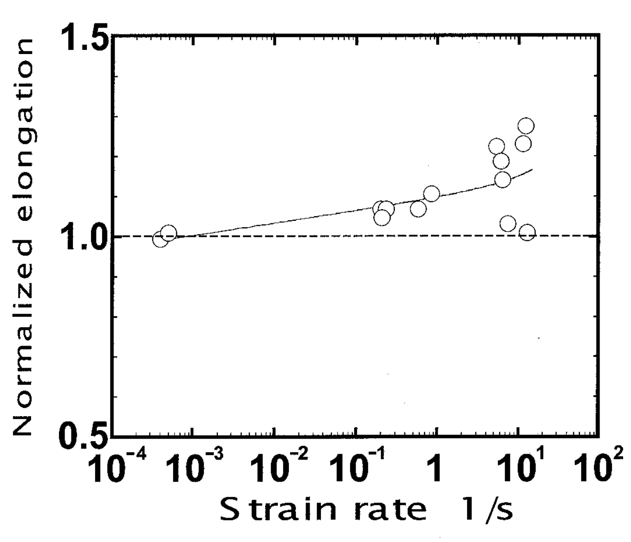


Fig. 19 Ultimate elongation vs. strain rate.

cable specimen. In the figure, the ultimate elongation is given by the normalized value with the averaged one from the static tensile test. As can be seen from **Fig.19**, the ultimate elongation increases clearly with the increase of the strain rate. At the strain rate of 5.0 (1/s) or higher rates, the strain rate effect becomes even larger. That is, at the strain rate of about 10.0 (1/s), the ultimate elongation is about 10% larger than that for the static tensile test. Based on the results shown in **Fig.19**, the ultimate elongation of CFRP cable is expressed by the function of the strain rate as:

$$\frac{e_d}{e_s} = \left(\frac{\varepsilon_d}{\varepsilon_s}\right)^{1.3\times10^{-2}} \times e^{(7.88\times10^{-7})\times\left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)} \qquad (2)$$

where e_d is the ultimate elongation (%) for a high-speed tensile load, e_s is the averaged ultimate elongation (%) for the static tensile test, $\dot{\varepsilon}_d$ is the strain rate (1/s) for a high-speed loading, $\dot{\varepsilon}_s$ is the strain rate (1/s) in the static tensile test, e.g., $\dot{\varepsilon}_s=10^{-4}$. Based on Eq.(2), the ultimate elongation-strain rate relation is given in **Fig.19** by the thin line.

3.2.5 Energy absorption capacity

The relation between the energy absorption capacity up to the tensile failure of CFRP cable for high-speed tensile load and the strain rates is shown in **Fig.20.**

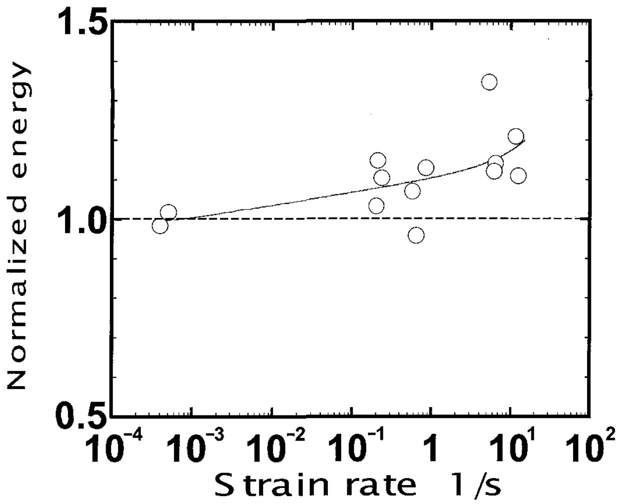


Fig. 20 Energy absorption capacity vs. strain rate.

The energy absorption capacity was calculated by a trapezoidal rule from the load-elongation relation. In **Fig. 20**, the quantity of absorbed energy for high-speed tensile load is normalized by that for static tensile load. It can be seen that the energy absorption capacity of CFRP cable increases with the strain rate increases. That is, at the strain rate of about 10.0 (1/s), the ultimate elongation is about 15% larger than that for the static tensile test. From results, when the energy absorption capacity of CFRP cable is related with the strain rate, its relation yields the following equation:

$$\frac{E_d}{E_s} = \left(\frac{\varepsilon_d}{\varepsilon_s}\right)^{1.32\times10^{-2}} \times e^{(1.5\times10^{-6})\times\left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)} \qquad (3)$$

where, E_d is the energy absorption capacity (N・m) for a high-speed tensile load, E_s is the averaged energy absorption capacity (N・m) for the static tensile test, $\dot{\varepsilon}_d$ is the strain rate (1/s) in a high-speed tensile loading, $\dot{\varepsilon}_s$ is the strain rate (1/s) in the static tensile test, e.g., $\dot{\varepsilon}_s=10^{-4}$. Using Eq.(3), the energy absorption capacity-strain rate relation is given in **Fig.20** by the thin line.

4. Conclusions

The goal of this study is to find fundamentally the dynamic tensile properties of CFRP cable subjected to high-speed tensile loads. Then the high-speed loading tests for CFRP cable specimens were executed. In tests, specimens were tested until the tensile breakage will occur. Based on test results, the tensile failure load, the elongation at breakage and the energy absorption capacity were examined and related with the strain rates of 10^{-4} to 10^{1} (1/s). The conclusions based on the experimental results presented in this paper are as follows:

1) The tensile stress wave, which is generated by the high-speed loadings, propagates to the whole length of CFRP cable and then concentrates at the near end of tab. The tensile breakage of strands will occur at either end of cable.
2) When the dynamic tensile properties of cable specimens subjected to high-speed loads or impact loads is to be examined, the fixing method of a cable specimen in tests should be improved or newly developed. As an example, the tip of a tab with a taper shape is recommended.
3) The load- elongation relations in the case of loading rates of 0.10 to 0.34 m/s are almost linear up to the breaking point in the same as that for the case of quasi-static loading. When the loading rate becomes larger than 1.17 m/s, the elongation of cable will be developed 0.5 ms behind the load. In dynamic tests, the load data measured by a load transducer is strongly affected by the inertia when the loading rate becomes larger.
4) The failure loads of CFRP cables under the conditions of the strain rates of less than 1.0 (1/s) slightly deteriorates compared to that for the static tensile test. When the strain rate becomes larger than 1.0 (1/s), the failure load remarkably deteriorates. At the strain rate of about 10.0 (1/s), the failure load is about 10% lower than that for the static tensile test.
5) The ultimate elongation increases with the increase of the strain rate. For the strain rate of 5.0 (1/s) or higher, the strain rate effect becomes even larger. At the strain rate of about 10.0 (1/s), the ultimate elongation is about 10% larger than that for the static tensile test.
6) The energy absorption capacity of CFRP cable increases with the strain rate increases. At the strain rate of about 10.0 (1/s), the energy absorption capacity is about 15% larger than that for the static tensile test.

Acknowledgements

The authors would like to express their gratitude to Prof. N. Ishikawa and Prof. S. Hino for valuable advice and discussions to this research and also grateful to Dr. M. Beppu, Mr. T.Yamaguchi and Mr. S.Eda, National Defense Academy, for their assistance in these experiments. Mr. H.Koyama, Mr. T.Koseki and other engineers of the Mechanical Training Center for their technical support for making experimental instruments and specimens are gratefully acknowledged.

References

1) S. Owada: Study about mechanical property of strand, Journal of Institute of In-

dustrial Science, University of Tokyo, pp.238-284, 1955 (in Japanese).
2) T. Hayashi: About correction mechanism in roll correction method of wire rod, No.1, Applied Dynamics Alliance Lecture, Nov.3, 1951 (in Japanese).
3) Mikulas, M. M., Jr. and Yang, L. F.: Conceptual Design of a Multiple Cable Crane for Planetary Surface Operations, NASA TM 104041, Jan. 1991.
4) Mitsugi, J. and Yasaka, T.: Nonlinear Static and Dynamic Analysis Method of Cable Structures, AIAA J., 29, pp.150-152, 1991.
5) K. Yamamoto: A Study on the Ground-based Shape Adjustment of Cable Net Antenna Reflectors, Proceedings of the 33th Structures Conference, pp.6-9, 1991 (in Japanese).
6) J. Mitsugi and A. Meguro: Dynamics of flexible multibody system including cables, Proceedings of the 37th Structures Conference, pp.219-222, 1995 (in Japanese).
7) Yang, L.: Damping Augmentation for Three-Cable Suspension System for Structural Testing, J. of Spacecraft and Rockets, 33, pp.292-297, 1996.
8) K. Kawada, M. Itabashi, H. Kimura and H. Ishigami: The tensile dynamical behavior of CFRP cable, Proceedings of the 36th Structures Conference, pp.37-40, 1994 (in Japanese).
9) Tokyo Rope Co. Ltd.: CFCC technical data, 1993 (in Japanese).
10) M. Hayashida: Use of the pitch series high elastic carbon fiber in the civil engineering and the architecture field, Journal of the Japan Society for Composite Materials, 25, 1, pp.30-37, 1999 (in Japanese).
11) Y. Iba, M.Uemura, S. Murakami M. Saito and A. Kobayashi: Development of the Forcatow sheet for repair / reinforcement of the civil engineering and the architectural structure, Journal of the Japan Society for Composite Materials, 25, 2, pp.73-83, 1999 (in Japanese).
12) I. Nishizaki: The trend of the use of FRP into the civil engineering structural material, Journal of the Japan Society for Composite Materials, 26, 2, pp.37-42, 2000 (in Japanese).
13) Edited by the Public Works Research Institute: The joint-research report about application of the fiber-reinforced plastics to the civil engineering structure material, pp.236-245, 1999 (in Japanese).
14) K. Yamaguchi, I. Kimpara and K. Kageyama: Experimental study of crack growth resistance of steel members repairing with externally CFRP sheets, JSMS COMPOSITES-29, pp.131-132, 2000 (in Japanese).
15) I. Okura, T. Fukui and T. Matsugami: Application of CFRP sheets to Repair of Fatigue Cracks in Steel Plates, JSMS COMPOSITES-29, pp.133-136, 2000 (in Japanese).
16) H. Nakamura et. al: Carbon Fiber Reinforced Plastic Rod for Shear Reinforcement of Concrete Structure, Proc. of the 3rd Japan Int. SAMPE Symposium, pp.230-234, 1993.
17) H. Motoyama, K. Shiga, K. Moriya and T. Ohta: Tensile tests of Carbon Fiber Composite Cables and Health Monitoring by Electrical Resistance Method, Journal of the Japan Society for Composite Materials, 28, 2002 (in Japanese).
18) H.Kimura, M.Itabashi and K.Kawata: Mechanical Characterization of Unidirectional CFRP Thin Strip and CFRP Cables under Quasi-Static and Dynamic Tension, Proceedings of the 9th US-Japan Conference on Composite Materials, pp.563-570, 2000.

19) Y.Kobayashi and Y.Tanaka: IMPACT TENSILE STRENGTH OF CARBON FIBER COMPOSITE CABLE, Advanced Composite Materials in Bridges and Structures 1st International Conference, pp.83-88, 1992.
20) Edited by the wire rope manual edit committee: The wire rope manual, Hakuashobo, Tokyo, pp.346-360, 1967 (in Japanese).