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Technique for Fabrication by Resistance Heating and Tensile Properties of CFRP Cables

by

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Abstract

This study is to propose the on-orbit fabrication of CFRP cable net structures by using the method of electrical resistance heating in order to construct large space structures in the near future. The on-orbit fabrication of cable net structures is accomplished by transporting coiled stock of prepreg of CFRP cable from the earth to the orbit and curing it by means of the resistance heating whose operating power is supplied by the solar electric power system. Laboratory tests indicate that CFRP cables can be cured uniformly and precisely with the specified cure cycle by controlling the low voltage current. Tensile tests for CFRP cables cured by the resistance heating as well as those of uncured ones have also been performed and the results show that the cured cables exhibit the high tensile strength and stiffness which are about two times higher than those of the uncured ones. In preparing for the tensile specimens of uncured cables, it has been found that any part of CFRP cables can be left uncured by the present method without changing the curing process. At these uncured portions, they can be bent for folding and be connected to other structural members with knots without using mechanical hinges or joints.

Keywords: Composite materials, CFRP cable, Cable network, On-orbit fabrication, Cure, Resistance heating, Tensile test

1. Introduction

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 present and future situation, the deployable structures should be 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. For instance, a parabolic antenna is consisted of 2000 staple cables and thus the 6000 of structural cables

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are used for the whole. This antenna was employed for a space Very Long Baseline Interferometer (VLBI) with the maximum diameter of 10 m mounted on the artificial satellite HALCA which was lunched by the Institute of Space and Astronautical Science in February, 1997[1]. If the strength of tension, bending, torsion and compression of cable net and tension truss members can be improved by the hardening treatment, it enables to improve the functional accuracy and reliability of space structures, and to construct the even larger structures. For an example, the hardening treatment of internal cable column of Inflatable Rigidized Structures (IRIS) that combined a membrane side with a cable network was proposed[2] and the curing tests for the composite material pipes were done. However, since the stowage capacity of a rocket and a space shuttle is limited, it is almost impossible to carry the prefabricated composite members to the orbit. For instance, a section of freight room of the space shuttle made in the U.S.A. has 4.6 m in diameter and 18.3 m in length. That is why, it is impossible to carry the structural members to the orbit if the size of cable structures is larger than the dimension of space shuttle.

To solve this problem, the procedure to cure the prepreg of CFRP (Carbon Fiber Reinforced Plastics) cable by using the Joule heat generated by flowing the current is proposed. Herein, the prepreg is the flexible bunch of carbon fibers impregnated the epoxy resin. Though the rolled prepreg of CFRP cable can be easily carried to the orbit, a large-sized cured CFRP cable can not be transported due to the limitation of space capacity in a rocket.

To this end, this paper is to present a fundamental technique of the on-orbit fabrication of CFRP cables by using the controlled resistance heating. In other words, this technique enables to construct the large-scale cable net structures in the space more effectively than on the ground since solar energy can be utilized directly. When this technique is materialized in the space field, the problems of the construction of large-scale and light-weight space structures, and the stowage efficiency at launching and structural accuracy after deployment, which are the opposite demand in a mutual relation, may be solved.

In this study, it will be found from the analyses that an actual size of CFRP cable with 10 mm in diameter can be cured by using the resistance heating, which is generated by flowing the current to cable fiber. And, to examine the change in the tensile properties of CFRP cable with resinous hardening, tensile tests for the cured CFRP cables and the prepreg of CFRP cable were executed.

In tensile tests for the prepreg of CFRP cables, both ends of a prepreg specimen should be completely cured to install in a tensile testing machine, and the specimen in which only the part to be tested should be kept as a prepreg state. However, it is quite difficult to make a cable specimen that it is not partially hardened if the old technique is applied. The new technique proposed in this paper is not a method that it is the autoclave or the press for thermosetting composite processing. Also, this technique is useful not only the tensile tests for prepreg specimens but also the process of connecting between the CFRP cables or other structural members. Since the process of bending the cured cables involves great difficulties, the mechanical metal fittings such as hinges or joints are required when the cable is folded and is put together to other members. If the joint and folding section of cables could be kept as a prepreg state, it is possible to connect by the use of knots or to fold as a prepreg state. Thereby, the structures may be lightened and the number of components can be remarkably reduced.

In the field of aeronautical engineering, many studies[3,4] related on the steel cables have been steadily done to examine the mechanical properties of them. In recent years, the application of cable networks, tension trusses and space tethers to deployable space structures have been studied[5-9]. Of these, the studies on CFRP cables are extremely few even though they are indispensable and important[11].

2. Fabrication of CFRP cables by using resistance heating technique

Carbon which is used for the carbon film resistor of electronics circuits is a conductor with the electric conductivity of about 5×10^4 S/m. The CFRP cable made by impregnating with a resin and twisting triple bunch of carbon fibers generates the Joule heat of i^2R per unit hour when electric current is flowed into fibers. Making use of this nature, it is possible to cure the matrix resin by controlling the change of prepreg temperature according to the curing schedule after flowed the current into prepreg directly and controlled the Joule heat quantity through the variation in the current i[12].

2.1 Temperature control and curing device

When the prepreg is being processed, temperature of CFRP cable is controlled by the Joule heat quantity which is adjusted by flowing the current. That is, the necessary electric power $V\cdot I$ for curing a cable is given by:

$$V\cdot I=K_p'\cdot Z \tag{1}$$

where, V is the voltage, I is the current, Z is the deviation of between T and T_r, i.e., $Z=T_r-T$, T is the temperature at present, T_r is the desired temperature, K_p' is the proportional gain.

Transforming Eq.(1), the supply current I for curing a cable can be obtained from the following equation.

$$I=\sqrt{\frac{K_p'\cdot Z}{R}} \tag{2}$$

where, R is the inter-electrode resistance and is calculated from both the flowing current I and the inter-electrode voltage V. Let R to be fixed, Eq.(2) is expressed by:

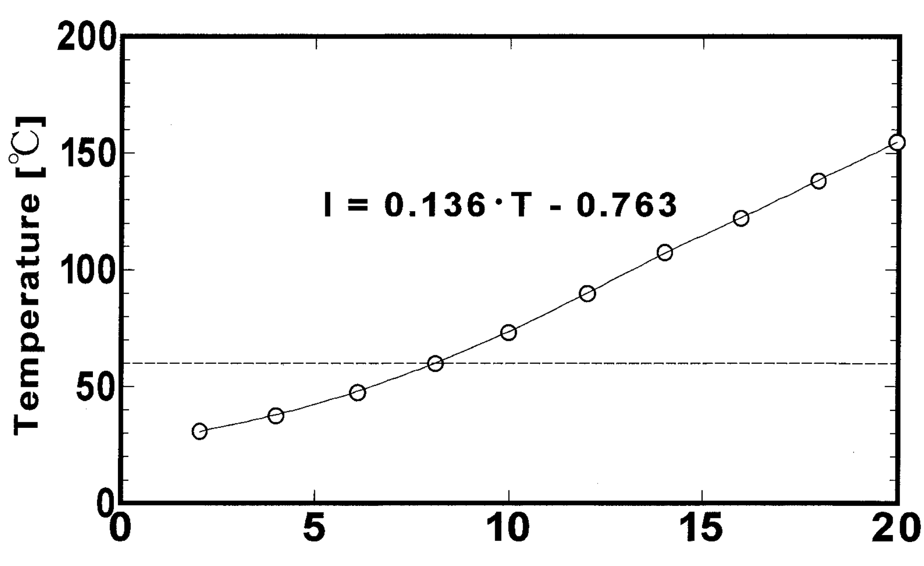

Fig. 1 Relation between flowing current and temperature of CFRP cable.

$$I = \sqrt{K_p \cdot Z} \tag{3}$$

where K_p ($=K_p'/R$) is the proportional gain. When the PID (Proportional Integral and Derivative action) control[13] is adopted to improve the control accuracy and to enhance the stability of control, the supply current I is determined by the following equation.

$$I = K_p\left[Z + \frac{1}{t_i}\int Zdt + t_d\frac{dZ}{dt}\right] \tag{4}$$

where, t_i is the integral time and t_d is the derivative time. These values (K_p, t_i, t_d) can be found from the method of Ziegler-Nichols[13].

In order to find the relation between the supply current and the temperature of prepreg, the prepreg cable with a length of 600 mm was tested by flowing the current while changing from 2 A to 20 A. During this test, a room temperature was maintained at 20 °C. The result obtained from this test is shown in **Fig. 1**. It can be found from the figure that the temperature above 60 °C increases almost in proportion to the quantity of flowing current. Thus, the relation of T vs. I is given by a linear function as Eq.(5). When the temperature at present T exceeds the desired temperature more than a certain deviation, the quantity of current I to be corrected can be given by Eq.(5). Then, the unusual generation of heat can be avoided.

$$I = -0.763 + 0.136 \cdot T \qquad (T \geqq 60\ °C) \tag{5}$$

When the temperature at present T is lower than 60 °C, the quantity of current calculated from Eq.(4) is flowed directly to the prepreg.

The prototype curing device shown in **Fig. 2** is consisted of a power supply control unit which controls the output current, a thermometry unit which measures the temperature, a system controller which gives an instruction to a power supply control unit through GP-IB interface, a loading device to apply the initial load to the prepreg and a electrode which serves as a grip. The flowed current is measured by using the non-contact current sensor in which Hall element was adopted, and the value of the flowed current is read through the

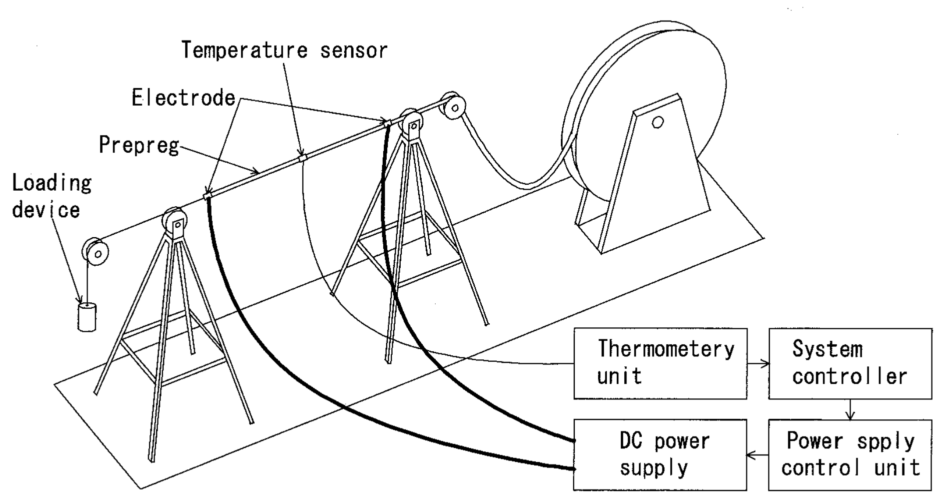

Fig. 2 Outline of curing device used in tests.

digital multimeter after converted the current I into the voltage V. The temperature of prepreg is read by the digital multimeter with 10 scanners, and then it is transmitted to the system controller through GP-IB interface. The T-type thermocouple is used as a temperature sensor, and a thermometry section of its tip was coated with a polyimide tape for the electric insulation and mold-release and was buried in between the strands of prepreg.

Both ends of the prepreg were gripped by the electrodes, and the current of amperage given by Eq.(4) is flowed between the electrodes. The present desired temperature T_r can

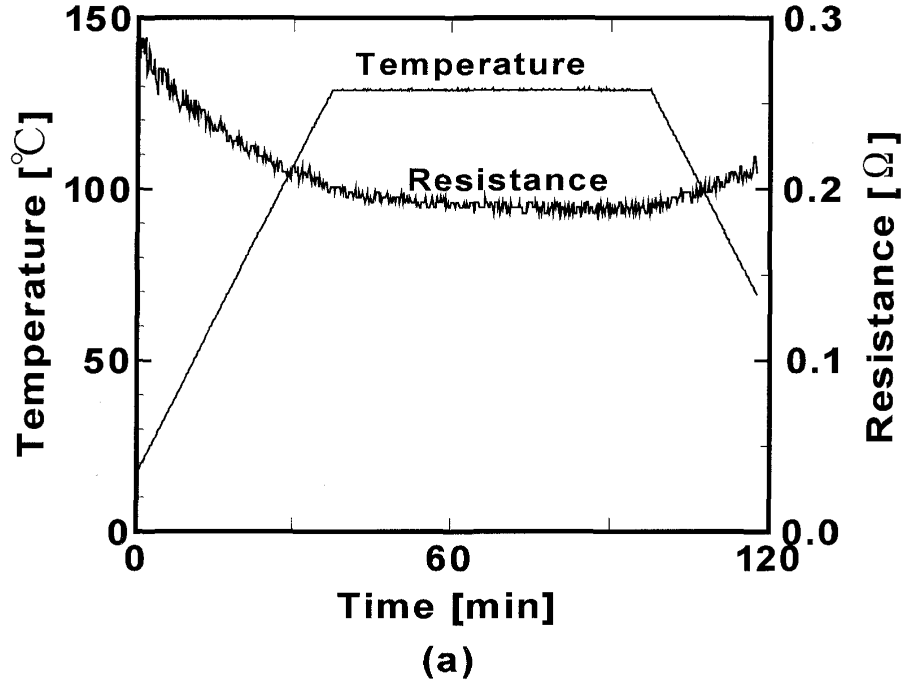

Fig. 3(a) Inside temperature and inter-electrode resistance-time relations of CFRP cable.

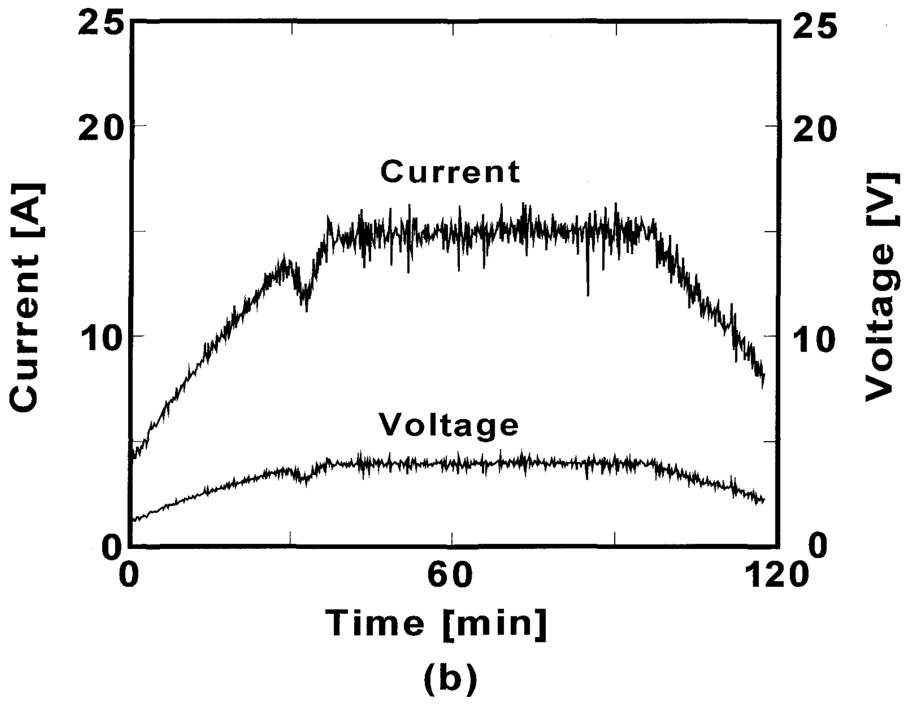

Fig. 3(b) Current and voltage-time relations of CFRP cable.

be calculated from both the elapsed time and cure schedule, and the inter-electrode resistance R is calculated from both the flowing current and inter-electrode voltage.

The load when a cable is straightened without elongation is called the initial load. To align the cured cable and to keep the prescribed pitch, the initial load of 100 N, which is given by a weight, is applied to one end of the grips.

2.2 Curing of test specimens

The prepreg of CFRP cable used for a test is made by twisting spirally three strands of Poly-Acrylo-Nitrile(PAN) series carbon fiber (Sumika-Hercules Magnamite AS2) impregnated with epoxy resin, which has the 7 mm in diameter (manufactured by Sumitomo Chemical Industries Co. Ltd.). After formed, CFRP cable has the fiber content of 60 % by volume, the nominal diameter of 10 mm and spiral pitch of 100 mm.

The basic cycle of curing resin is to raise the initial temperature up to 130 °C by 3 °C per minute and to keep 130 °C for 30 to 60 minutes, and then to reduce temperature by 3 °C per minute. **Fig. 3** shows an example of the relations between time and temperature, inter-electrode resistance, current and voltage respectively, when the cured CFRP cable was at the holding temperature of 130 °C. Although the curing process was scheduled by a simple rule, it is found from that the temperature was well controlled in the whole process which includes the shifting process from raising to holding the temperature and the change of flowing current with time was gentle in the whole process, and that the supply power decreased the corresponding amount to the heat of reaction due to the curing of resin just before shifting from the heating phase to the holding phase. **Fig. 4** shows the distribution of surface temperature, which was measured by the emission thermometer at the phase of holding temperature, in the direction of the spindle line of the cable with the overall length of 0.6 m. It can be found from **Fig. 4** that the surface temperature in the prepreg was kept almost uniformly at the holding temperature 130 °C except in its end. In the temperature distribution shown in **Fig. 4**, the wavy curve was appeared due to the unevenness of cable surface and

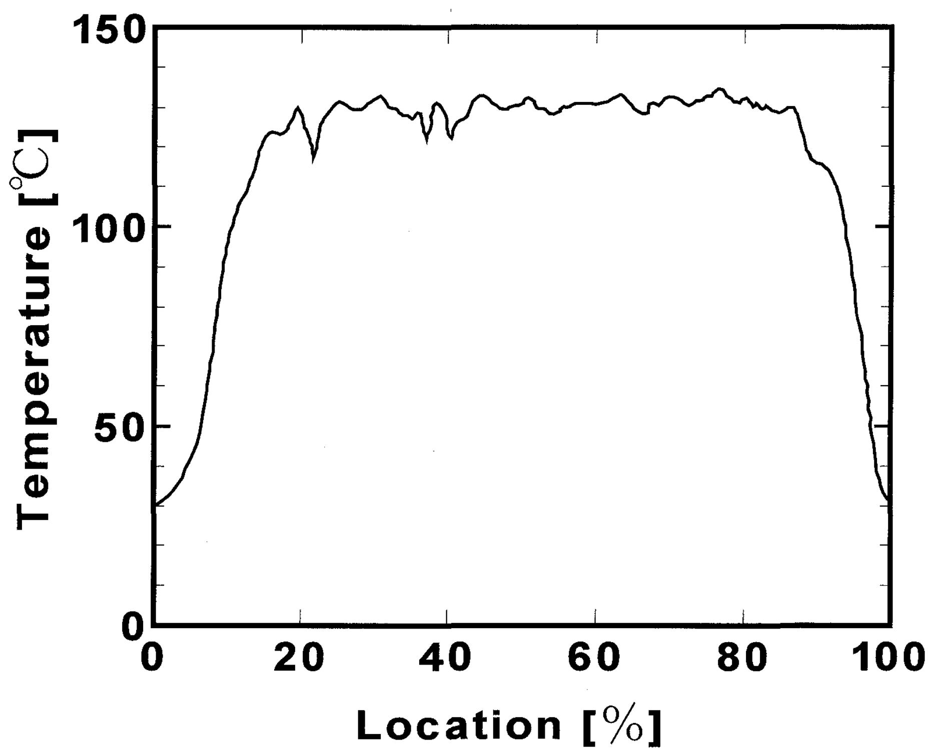

Fig. 4 Surface temperature distribution of CFRP cable (prepreg) while curing.

the crossing of the wires of five thermocouples arranged in an equal interval between a cable and an emission thermometer. And, the temperature at the neighborhood of both ends of cable decreased rapidly and that at the electrode and the grip section were almost low enough to touch by hand. It may be cleared that the technique presented herein is useful and applicable to cure the CFRP cable by using the solar power generation on the orbit since it is possible to cure the cable with the nominal diameter of 10 mm through the low voltage of about 4 V per one meter.

Next, to evaluate the degree of progression in the curing reaction of specimens, the heat analyses by the use of the differential thermal analyzer (DTA, TGD5000-S-RH, by Shinku-riko) were performed to the samples of finely powdered CFRP cable which was made by changing the curing temperature from 80 to 150 °C and the prepreg CFRP. The differential thermal analysis is a method of examining the thermal difference between the temperature of specimen and that of the standard material generated by cooling and heating under the equal condition. Also, the atmospheric temperature should be measured.

When two contact points of thermocouples are respectively inserted into a sample and a standard material, the heat electromotive power with the quantity proportional to the difference in temperature can be obtained. This voltage difference produces the heat of reaction. In this study, the alumina (Aluminum oxide, Al_2O_3) was used for the standard material. The degree of progression in hardening reaction of an epoxy resin[14,15] is expressed by the glass transition temperature T_g or the rate of reaction ξ which are obtained from the differential thermal analysis. Generally, since the glass transition temperature T_g of thermosetting resin, e.g., the epoxy resin, becomes high, the degree of progression in hardening reaction can be estimated from T_g. The rate of reaction ξ is obtained by comparing the change of reaction heat with time of a sample and a prepreg. When the hardening reaction has been in progress, the reaction heat of uncured resin is detected by the differential thermal analysis. The rate of reaction ξ is given by

$$\xi=(\Delta H(0)-\Delta H_r)/\Delta H(0) \qquad (6)$$

where, $\triangle H(0)$ is the reaction heat of prepreg and $\triangle H_r$ is the reaction heat required to finish the hardening reaction of the fabricated sample[16]. The standard material and a sample of 90 mg in weight were used for the differential thermal analysis. Tests of each specimen were done for two times according to the prescribed schedule as raising from the normal temperature to 250 °C by 8 °C per minute and then reducing by 8 °C per minute. In the first one cycle, the uncured resin is hardened and then the hardening reaction may be completed. That is, the difference caused by the result in the second cycle is the reaction heat of uncured resin. The relation between the curing temperature and the glass transition temperature T_g and also the relation of the curing temperature and the rate of reaction ξ are shown in **Fig. 5**.

The glass transition temperature and the rate of reaction increase with the increase of curing temperature. And, there are great differences in the rate of reaction between two samples by cured respectively at the temperature of 80 °C and 90 °C. This shows that the degree of hardening reaction depends on the curing temperature.

3. Tensile test of CFRP cable

In order to examine the validity of resistance heating method proposed in this study and the influence of resinous hardening on the tensile properties of CFRP cable, tensile tests for

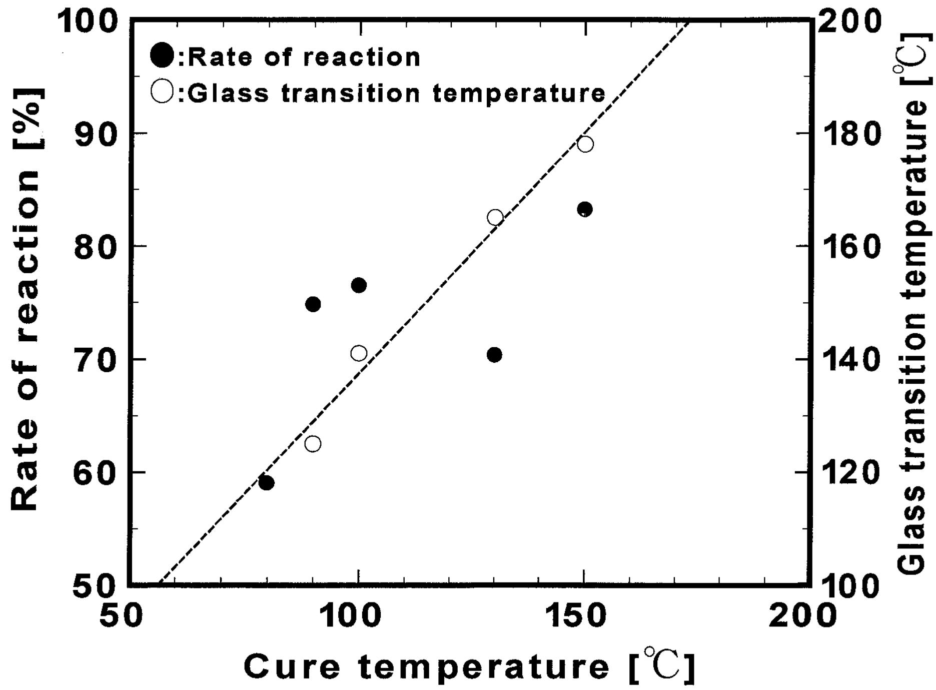

Fig. 5 Rate of reaction and glass transition temperature vs. cure temperature.

the cured cables by this technique and by the autoclave and the prepreg of CFRP cable were done. Tensile tests for the cables cured at 80, 90, 100, 130 and 150 °C were also conducted. The fiber contents of all cables, which were measured by the combustion method, were 60 % by volume as the nominal values shown in a mill sheet.

3.1 Specimens for tensile tests

As shown in **Fig. 6**, the specimen has 200 mm in gauge length and 500 mm in full length. Both ends of cable were inserted into the tabs, which is made of mild steel, with the outside diameter of 25 mm, the inside diameter of 14mm and 150 mm in length. Then, both the end tabs were filled with the epoxy resin adhesive (Cemedine 1500). A specimen was installed in a correctional device to align and the adhesive was hardened under room temperature. The inside of tab has a female screw of M14 to strengthen the fixation. Specimens cured by 80 °C and 90 °C are lusterless compared to that by 130 °C. This may be indicated that the resinous hardening of surface was not completed. The curing conditions and the number of specimens are given in **Table 1**.

Since the sectional shape of uncured prepreg is not uniform, it is required to reinforce both ends of the prepreg cable with metal tabs so as to put it through the tensile test. Also to attach a tab to the end of uncured prepreg, the impregnated resin in the both ends of cable should be hardened in advance. In other words, in order to make a prepreg specimen for tensile tests, the resin of both ends of a cable inserted into a tab should be hardened while keeping the gauge mark between tabs in the prepreg state. The necessary heat quantity by the resistance heating method is much smaller than that by the external heating methods (autoclave, press etc.). Accordingly, if a part of prepreg is put along a device having the large quantity of heat capacity and is cooled with water, the temperature of both ends becomes equal to the circumferential temperature and the hardening of resin can not proceed. Such a manner as described before, it may be involved great difficulties in curing the prepreg specimen when the external heating method is used.

This technique can be used for not only the tensile test but also folding the CFRP cables and connecting to other structural members. In the case that the cured cable is folded or connected to other members, the mechanical hinges or joints are required for connection since the cured cable has difficulty in bending process. If a part to be connected or folded has been left uncured, it enables to connect cables each other by knots without metal fittings and to fold the cable itself. As a matter of course, the uncured part will be cured after the connecting process was finished.

3.2 Method of tensile test

Tensile tests were conducted with the crosshead speed of 2mm/min using the Shimadzu Autograph AG-25TE tensile testing machine, which has the loading capacity of 250 kN. If there is no restriction to rotate the metal fittings, a cable specimen subjected to a pulling load rotates to untwist direction. In this test, the rotation of specimen is completely restricted. **Fig. 7** shows the outline of measuring system in this tensile test. The load is measured by either two load cells, the loading capacities of 100 kN and 250 kN respectively, according to the test conditions. The elongation of a specimen is the change of length in the spiral pitch of 100 mm and is measured by the Shimadzu slit laser extensometer SLE-01. The output data from the load amplifier and displacement indicator are recorded into the personal computer through AD converter. The detected AE (Acoustic Emission) in tests were measured by using 4 channel AE analyzer (PAC3000/3004). Though the cable specimen is consisted of three strands, two AE sensors are installed on the one strand of cable and the location rating of AE signal's sources are examined by the arrival time differential method.

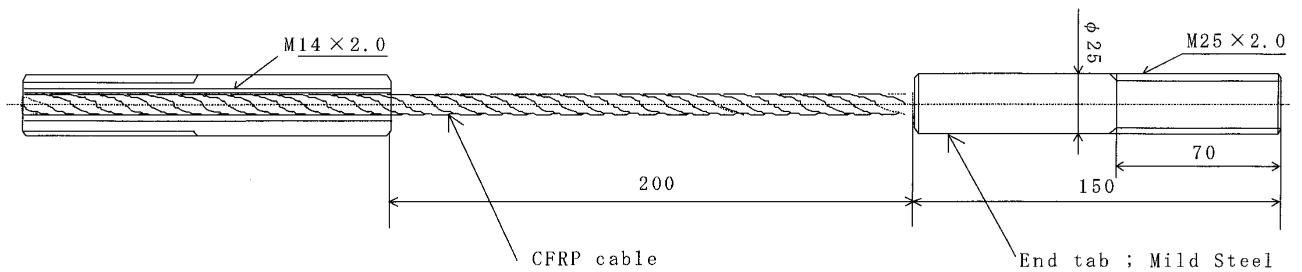

Fig. 6 Geometry of specimen for tensile test.

Table 1 Curing conditions and number of specimens.

No.	Curing conditions			Number of specimens
1	CFRP cable	prepreg state		2
2		Cure temp.	80℃	3
3			90℃	2
4			100℃	3
5			130℃	6
6			150℃	3
7		autoclave		3

3.3 Tensile test results

The results of tensile tests are summarized in **Table 2**. In the table, each value is given as the average for the number of specimens. **Fig.** 8 shows a typical example of the load-crosshead displacement relations in tensile tests. In the figure, a broken line shows the result for the cured CFRP cable and a solid line shows that for the prepreg. The load of cured cable increases in proportion to the crosshead displacement up to the load of 100 kN. And, when the load reaches the maximum load carrying capacity of cured cable, all strands break instantly at one part in a cable. Small cracks and longitudinal splits are appeared in the broken section as shown in the left side of **Fig. 9**. Even though the high load of 100 kN was released instantly, damage was centered at the fracture section. And the cable was not unbraided and was not aparted to pieces. This is different very much from the properties of a CFRP plate with one directional layer materials.

On the other hand, it can be seen from **Fig.** 8 that three peaks were appeared in the

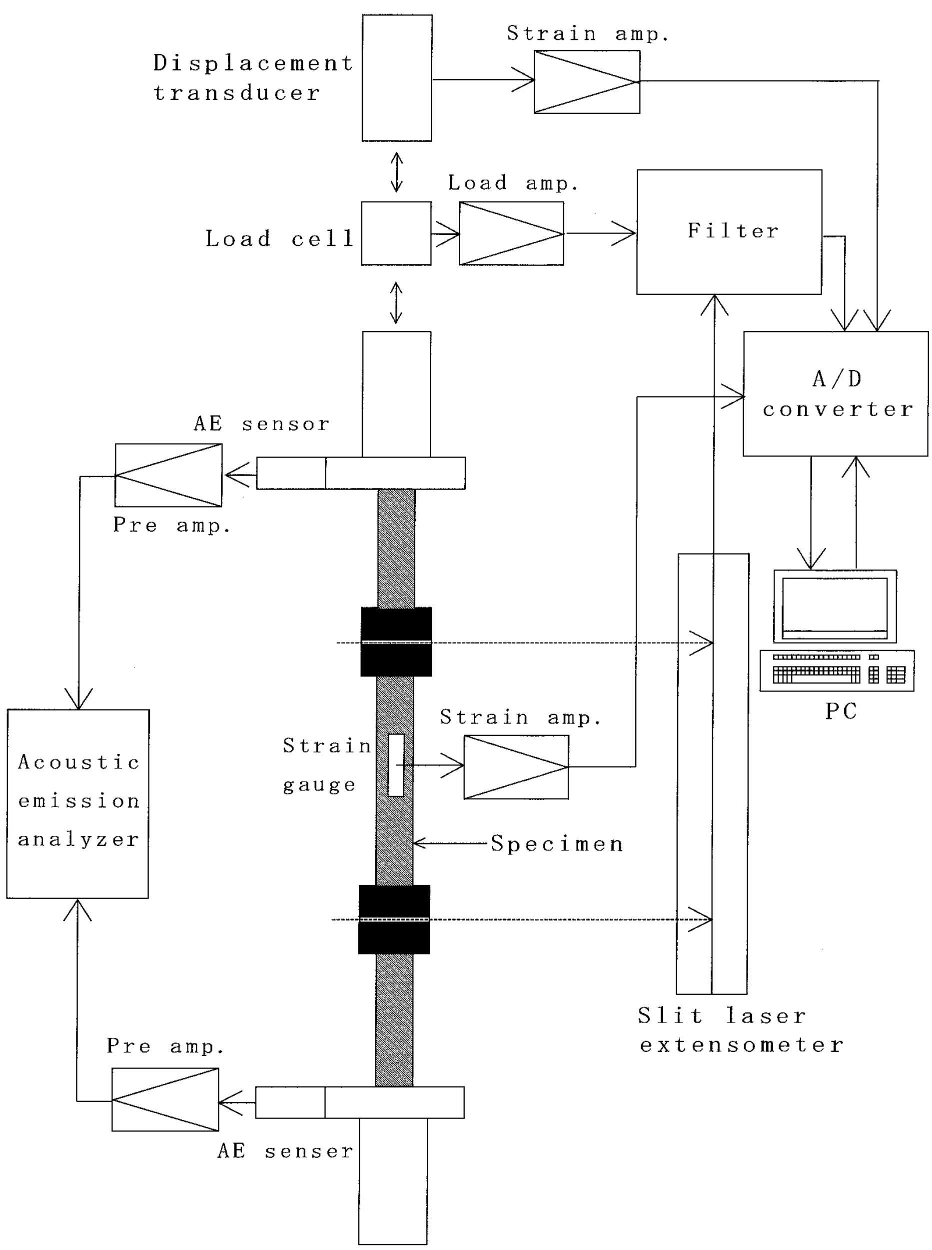

Fig. 7 Outline of measuring system in tensile test.

Table 2 Results of tensile tests.

Specimen No.	Tensile strength (MPa)	Longitudinal modulus (GPa)	Elongation (%)
1	751	53.1	1.41
2	710	62.0	1.14
3	1294	106.2	1.22
4	1408	109.6	1.28
5	1297	112.0	1.16
6	1362	115.1	1.18
7	1288	115.6	1.11

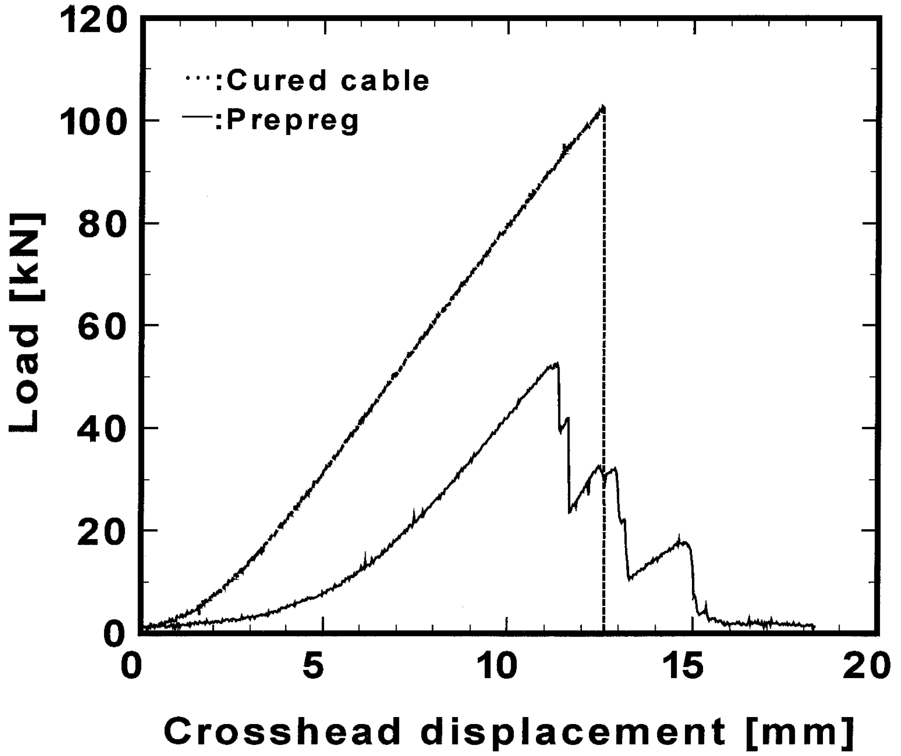

Fig. 8 Load-crosshead displacement relation of CFRP cable and prepreg.

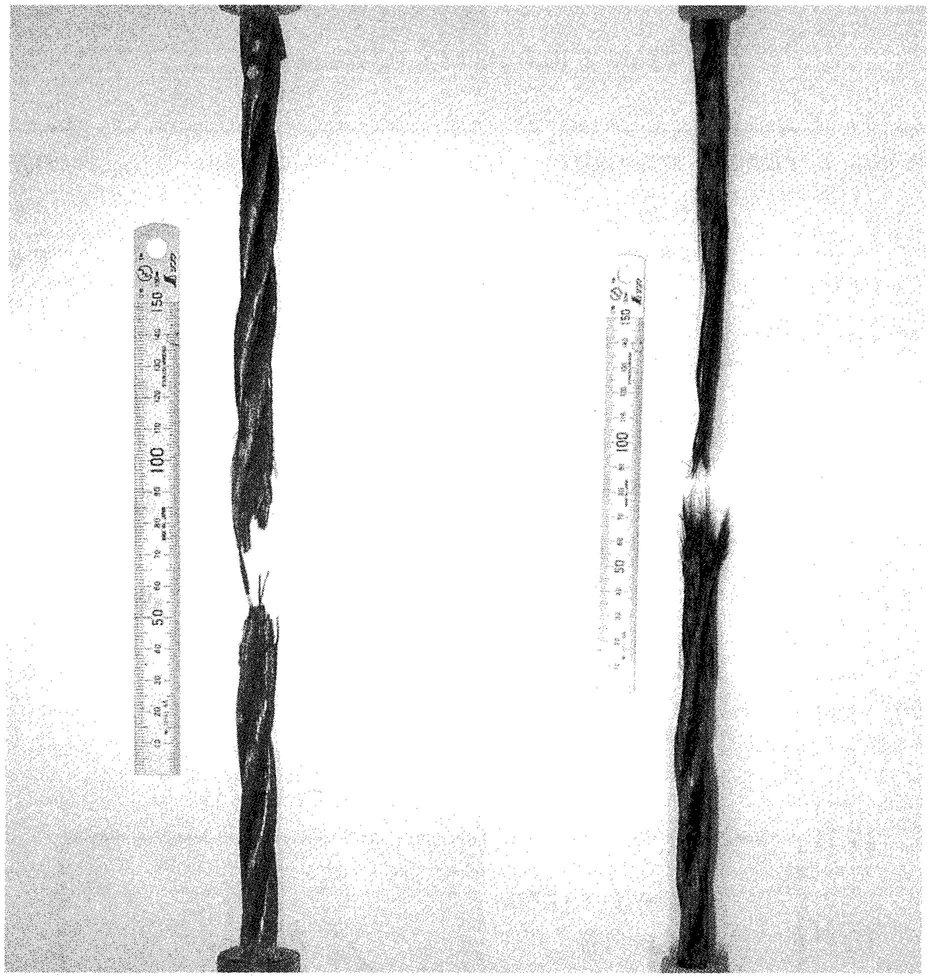

Fig. 9 Failure modes of CFRP cable (left) and its prepreg (right).

load-displacement relation of the prepreg. It is considered that each peak corresponds to the happening of fracture in each strand. That is, when one of three strands is broken, the load decreases in a moment. Then, the remained two strands bear the applied force and the load increases again linearly. This process is repeated until all strands are broken. Since fibers, which are the element of the strands, break in succession in everywhere within the gauge length before breaking a strand in the prepreg, the fracture of fibers were appeared in a wide area. This may be the reason that the load bearing by fibers may be dispersed over a certain range since fibers can move freely without restraint by resin. For another reason, it can be found from the fact that the number of AE outbreaks in the prepreg cable was much larger than that in the cured cable and AE sources estimated from the arrival time differential method were widely distributed between sensors. In tensile tests for the prepreg cable specimens, since the prepreg specimen has been kept almost the original shape even though it has been already broken due to the high adhesive effects of resin, it is hard to judge visually when a specimen was broken. After lifted the crosshead and pulled apart the broken specimen, it is observed that the broken section becomes a tip of sharpened brush as shown in the right hand side of **Fig. 9**. Fracture surfaces of the broken specimens were examined through the Scanning Electron Microscopy (SEM). In the specimen cured by above 90 °C, very few stuck of resin to the exposed interface was observed. In the specimen cured by the temperature of under 80 °C, it was observed that many roundish pieces of resin were stuck to the surface of fibers and this may be the cohesive failure mode.

The relationships between the curing condition of CFRP cables and the failure load and

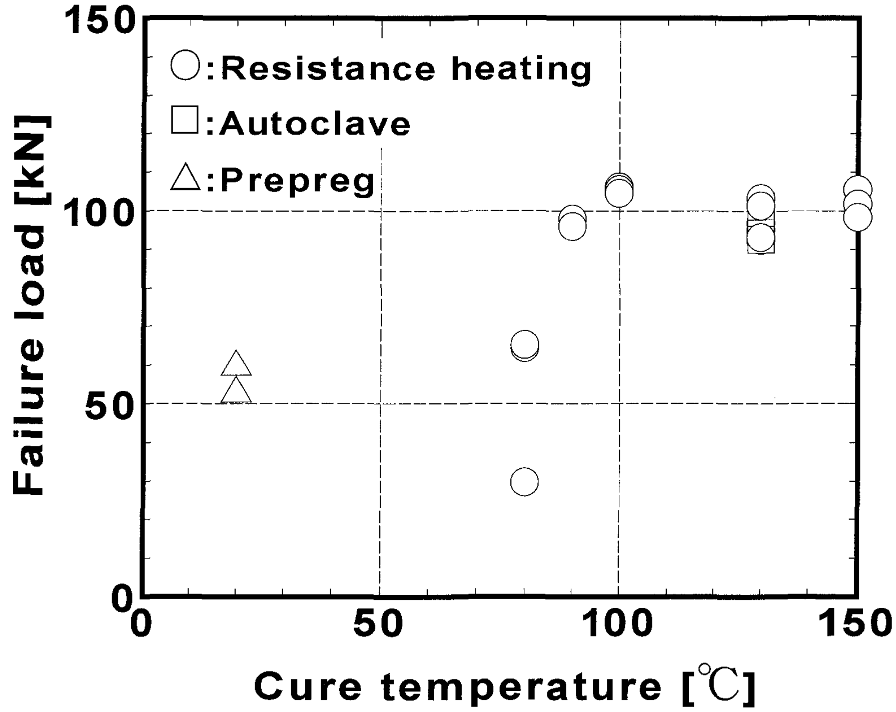

Fig. 10 Relation between curing condition and failure load of CFRP cable.

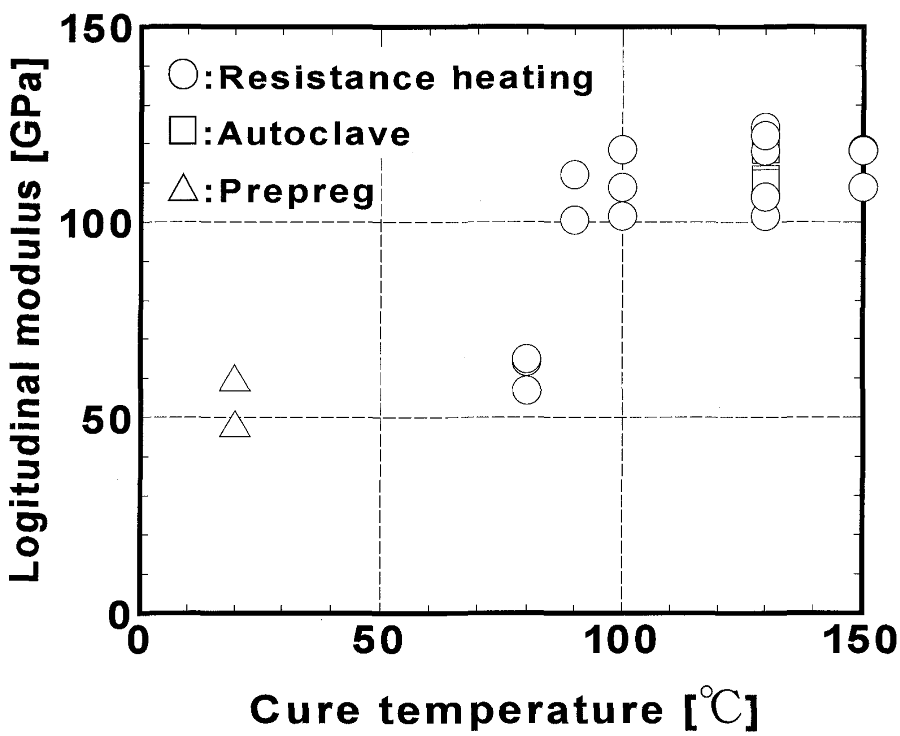

Fig. 11 Relation between curing condition and longitudinal modulus of CFRP cable.

between the curing condition and the longitudinal modulus are shown in **Figs. 10-11**, respectively. The longitudinal modulus is obtained from the calculation that divides first the failure load by the nominal cross section area of cable and then divides it by the failure strain measured by the laser displacement indicator. Some of physical properties of a CFRP cable

can be evaluated from these figures as follows.
1) Tensile properties of the cured cables are greatly influenced by the curing temperature of 80 to 90 °C.
2) The tensile strength and the longitudinal modulus of the cured CFRP cable is 2 times large as that of the uncured cable.
3) To gain the tensile properties of cable, the prepreg temperature at curing should be kept at above 100 °C.
4) The tensile properties of the cable cured by the method of resistance heating is equivalent to that of the cable cured by the autoclave.

4. Conclusions

In the near future, the large-sized space structures with a small capacity of stowage should be required. To meet the needs of the times, this study is to propose a technique of the on-orbit fabrication of CFRP structures by making use of the resistance heating. From this study, it is found that it is very effective to cure an actual size of CFRP cable with 10 mm in diameter by the resistance heating. And also found from tensile tests, it enables to improve and strengthen the tensile properties of CFRP cable by performing the curing treatment.

The following conclusions can be drawn from the results.
1) Temperature distribution in CFRP cable can be well controlled and it becomes almost uniform for the full length by flowing the current into the prepreg directly. By employing the method of temperature control, it enables to cure cables according to a cure schedule in which neither overshoot nor undershoot is happened. The CFRP cable with the nominal diameter of 10 mm can be cured by the low voltage of about 4 V per one meter in the atmosphere where the heat dispersion is large. Therefore, this method, of which the solar power generation is to make use, may be suitable for curing of CFRP cables on-orbit.
2) The quantity of heat generation required to cure cables by the proposed method is much smaller than that by the external heating system. Therefore, it enables to make the prepreg state in a part of specimen by cooling the uncured part while heating. If the length to be examined in a specimen has been left uncured and both ends of a cable is only cured, the prepreg specimen for tensile tests can be made. If this method is used, it is possible to connect the CFRP cables each other or with other structural members without mechanical hinges or joints and to fold them without difficulties.
3) The load of cured cable increases in proportion to the crosshead displacement up to the maximum load carrying capacity. And, when the load reaches the maximum load of cured cable, all strands break instantly at one part in a cable. Even though the high load was released instantly, damage was limited at the fracture section. And the cable was not unbraided and was not aparted to pieces. On the other hand, three peaks were appeared in the load-displacement relation of the prepreg. It is considered that each peak corresponds to the happening of fracture in each strand. That is, when one of three strands is broken, the load decreases in a moment. Then, the remained two strands bear the applied force and the load increases again linearly. This process is repeated until all strands are broken
4) Tensile properties of the cured cables are greatly influenced by the curing temperature of 80 to 90 °C. And, the tensile strength and the longitudinal modulus of the cured CFRP cable is 2 times large as that of the uncured cable. To gain the tensile properties of cable, the prepreg temperature at curing should be kept at above 100 °C. The tensile properties of the cable cured by the method of resistance heating is equivalent to that of the cable cured by the

autoclave.

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