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Makoto Saito , Akira Kobayashi & Shinkichi Murakami

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Reinforcement of structures using the FORCA Tow Sheet method

MAKOTO SAITO *, AKIRA KOBAYASHI and SHINKICHI MURAKAMI

Tow Sheet Division, Nippon Steel Composite Co., Ltd., Ohara Building, 3-8 Nihonbashikobuna-cho, Tokyo 103-0024, Japan

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Abstract—The FORCA Tow Sheet method is a method to reinforce concrete structures using FORCA Tow Sheet (carbon fiber sheet) which was developed by Tonen Corporation and is currently available from Nippon Steel Composite Co., Ltd. The method won a 'Fine Technology Prize' from the Japan Society of Composite Materials in 1997. In this method, the carbon fiber sheet is bonded to the concrete surface with an ambient temperature cure resin. The use of this method to repair or reinforce concrete structures has spread rapidly as it requires less time, reduces the cost of incidental work, and subsequently cuts labor costs through improvements in work efficiency.

Keywords: Carbon fiber; sheet; repair; concrete structure.

1. INTRODUCTION

Since the late 1980s, demand for carbon fibers in the fields of aeronautics, space, and sport equipment has steadily increased. High-elongation, high-strength carbon fibers for use in aircraft were mainly based on PAN, whilst high-modulus carbon fibers used in golf clubs to increase shaft rigidity were largely based on pitch. At that time, consumption of carbon fiber as a general structural material was still not very large — about 10 000 tons per year worldwide.

Starting in the mid 1980s, the use of so-called high-performance carbon fiber in civil engineering and construction applications began to be actively investigated. By the start of the 1990s, high-performance carbon fiber was being widely used in place of steel to repair or reinforce concrete structures such as bridges.

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*To whom correspondence should be addressed. E-mail: m-saito@nick.co.jp

method won a ‘Fine Technology Prize’ from the Japan Society of Composite Materials in 1997. In this method, the carbon fiber sheet is bonded to the concrete surface with an ambient temperature cure resin. The use of this method to repair or reinforce concrete structures has spread rapidly as it requires less time, reduces the cost of incidental work, and subsequently cuts labor costs through improvements in work efficiency.

2. FORCA TOW SHEET

The FORCA Tow Sheet method has typically used an epoxy resin to bond the carbon fiber sheet onto the concrete surface. The carbon fiber sheet used in this method is available in two types as shown in Fig. 1: interlaced carbon fiber sheet and unidirectional carbon fiber sheet. The term ‘high-performance carbon fiber’ refers to PAN or pitch based carbon fiber (so-called ‘HP-class’ carbon fiber). General-purpose carbon fiber (so-called ‘GP-class’) is not included within this category. The interlaced carbon fiber sheet is characterized by the carbon fibers being oriented in two directions at right angles to one another, i.e. 0/90°. This means that a single layer of interlaced carbon fiber sheet permits the structure to be reinforced in two directions simultaneously. However, the amount of carbon fiber in either direction is one-half of that in the unidirectional carbon fiber sheet. In addition, woven threads in the sheet and the resulting slight misalignment of the fibers also leads to some reduction in strength.

The unidirectional carbon fiber sheet consists of carbon-fiber tow fixed onto a release-coated paper with adhesive or knitted with glass-fiber weft or else fixed with a net on one or both sides (see Fig. 1b).

Traditionally, cold-setting epoxy resin has been used to bond FORCA Tow Sheet to the concrete surface. Recently, however, a special type of resin based on MMA chemistry has been introduced, particularly when the ambient temperature is low.

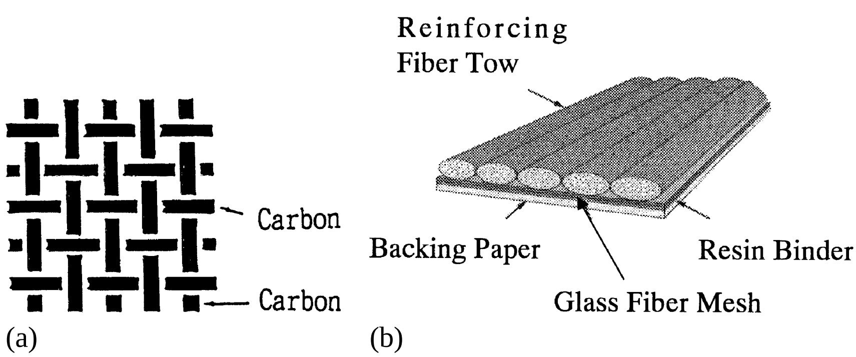

Figure 1. Types of carbon fiber sheet: (a) bidirectional type; (b) unidirectional type.

3. STANDARDS

Standards of carbon fiber sheets and resins have been unified by a trade organization under the guidance of the Ministry of Construction. The Carbon Fiber Repair and Reinforcement Research Association (CFRRA) has a total of 21 member companies: three materials manufacturers (Nittetsu Composite, Mitsubishi Chemical, and Toray Industries), five leading general contractors (Shimizu, Ohbayashi, Taisei, Takenaka, and Kajima), together with consulting firms and major builders. One important aspect of the carbon fiber sheet related standards is the concern with brittle fracture of the carbon fiber. The standard set by CFRRA stipulates that the design strength of carbon fiber shall not be greater than the average strength of the carbon fiber minus three standard deviations (see Fig. 2).

4. FEATURES AND APPLICATIONS OF THE FORCA TOW SHEET METHOD

Carbon fiber has both a lower density and higher strength and elasticity when compared with steel sheet. The tensile strength of carbon fiber is 10 to 15 times that of steel sheet, whilst the elastic modulus of carbon fiber is approximately 1 to 3 times that of steel sheet. A suitable type of carbon fiber is selected according to the reinforcement method used. In the FORCA Tow Sheet method, carbon fiber sheets are bonded to the concrete structure surface with ambient temperature setting epoxy resin (or MMA resin) in order or reinforce the structure. Features of the FORCA Tow Sheet method are as follows;

- The sheet can be easily cut to the shape of the structure to be reinforced.
- The process is simple, involving only bonding and impregnating of the sheet with resin.
- No heavy tools are required for the work and it can be done by hand hence the required working space is small.

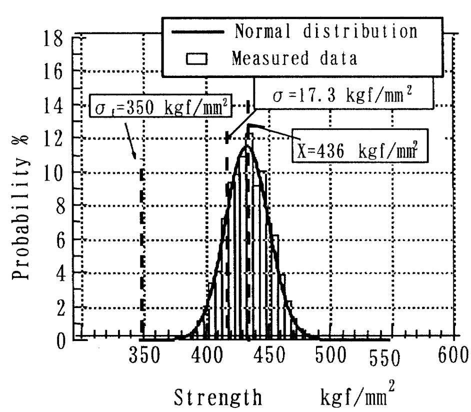

Figure 2. Strength distribution.

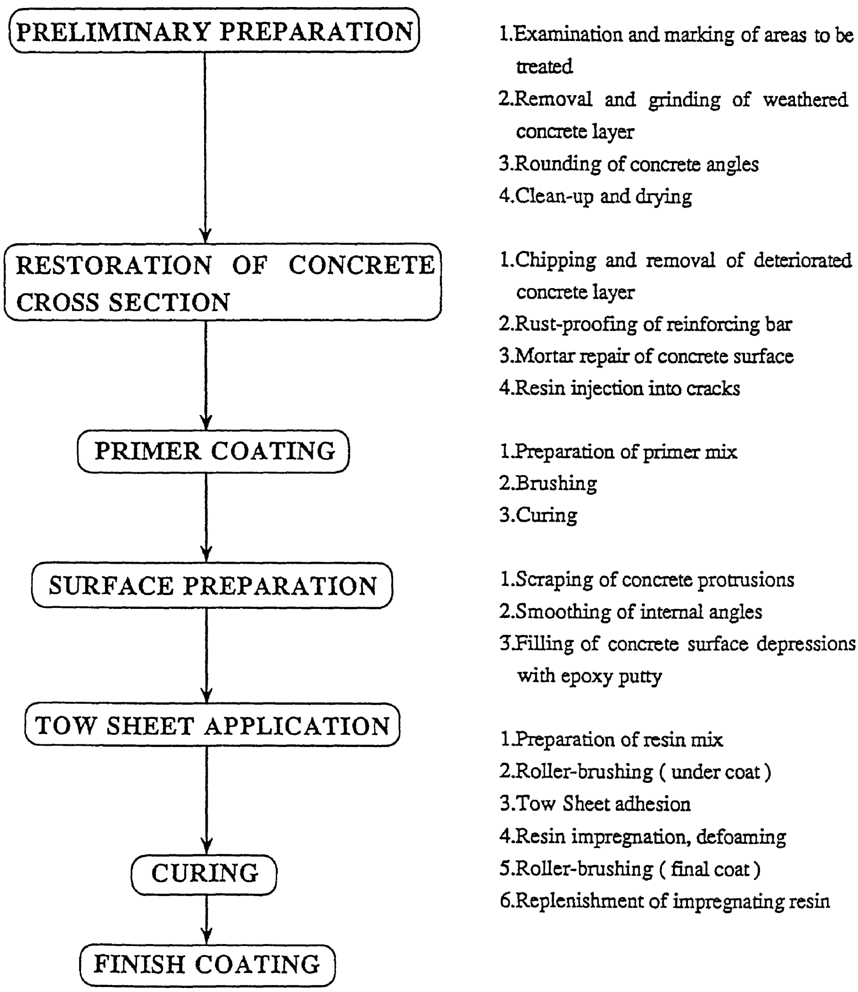

Figure 3. FORCA Tow Sheet application procedures.

- The process can be carried out by a small number of people in a shorter length of time compared to when steel sheet reinforcement is used.
- Since the carbon fibers are arranged unidirectionally, they provide high strength and offer the same degree of reinforcing effect as does steel sheet reinforcement.
- The only materials used are carbon fiber and resin and both are free from corrosion.
- Since the carbon fiber sheet with resin is a moisture barrier, it also helps to reduce degradation of the concrete and corrosion of the steel reinforcement.
- Since the black carbon fiber absorbs ultraviolet rays, deterioration of the epoxy resin due to ultraviolet rays is minimized.

The procedure used to apply the FORCA Tow Sheet is illustrated in Fig. 3.

5. REINFORCEMENT EFFECTS OF FORCA TOW SHEET

When FORCA Tow Sheets having the above characteristics are used to reinforce an RC structure, it is possible to determine the required number of sheets and directions in which to bond the sheets based on design calculations performed in the same manner as for steel sheet reinforcement. When FORCA Tow Sheet is bonded to a concrete structure, the following favorable effects should be expected regarding the reinforced concrete:

- Increased flexural capacity.
- Increased shear capacity.
- Increased constraining force.
- Prevention of cracks.

5.1. Improvement of beam flexural capacity

By bonding carbon fiber tow sheet to the tension side of a floor slab or beam subject to bending loads, it is possible to increase the flexural rigidity of the member and decrease the stress with the existing reinforcement. Even when the existing reinforcement fails due to a bending load, the carbon fiber tow sheet, as an elastic material, bears the tensile force, and thereby improves the flexural capacity of the member [1].

In order to confirm the reinforcement effect of carbon fiber tow sheet bonded to an RC beam and determine whether or not reinforcement of an RC beam can be designed in the same way as for reinforcement with steel sheets, RC beam specimens with carbon fiber tow sheets bonded in various configurations to the lower surface were subject to a four-point bending test. The carbon fiber tow sheet used in the test was a high-modulus type (50 tf/mm^2). Tow sheets were bonded longitudinally to the lower surface of beam specimens as shown in Fig. 4 with test results being given below.

Load–deflection curves at the beam center have been presented in Fig. 5 where it is evident that the figure from the yield load of the reinforcement varies according from that to the number of layers of bonded carbon fiber tow sheet. Compared to a beam specimen without tow sheet reinforcement (reference specimen), yield loads of specimens reinforced with one layer of tow sheet increased by 1.3 times whilst specimens reinforced with three layers increased by 1.8 times. With respect to the maximum yield strength, a specimen with one layer of tow sheet shows a value twice that of the reference specimen, whilst a specimen with three layers of tow sheet bonded longitudinally to the lower surface and one layer bonded transversely to the sides and bottom showed a value 3.1 times that of the reference specimen. From these results, it can be seen that by bonding tow sheets longitudinally to the lower surface of the beam and then bonding a tow sheet transversely to the two sides and bottom of the beam, the fixing force of the longitudinal tow sheets increase, thereby improving the maximum yield strength of the beam. This is an optimal use of the tensile strength of carbon fibers.

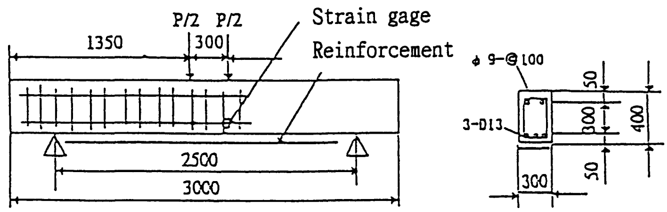

Figure 4. RC structure for evaluation.

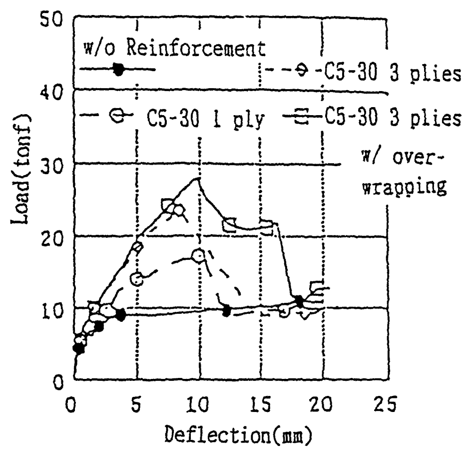

Figure 5. Deflection of tension member.

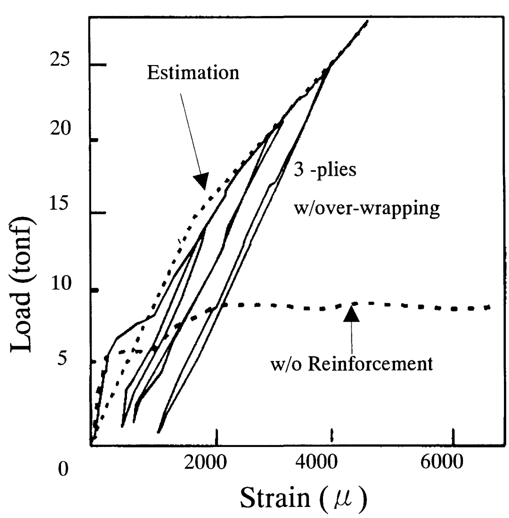

Figure 6. The result of bending beam test.

Figure 6 shows the relationship between load and center beam strain for the reference specimen and specimen reinforced with three layers of tow sheet bonded to the lower surface. The broken line in the figure represents calculated values and it can be seen that the experimental results agree well with calculated data. From

Table 1.
Properties of FORCA tow sheet

Type	Carbon fiber tow sheet				Glass fiber
Grade	HT carbon	HT carbon	HM carbon	HM carbon	E-glass
Fiber	FTS-C1-20	FTS-C1-30	FTS-C5-30	FTS-C6-30	FTS-GE-30
Fiber density(g/cm^3)	1.82	1.82	1.82	2.10	2.55
Fiber ariel weight(g/m^2)	200	300	300	300	300
Sheet width(cm (in))	50 (20)	50 (20)	50 (20)	50 (20)	50 (20)
Tensile strength					
kg/cm of sheet width	390	590	500	360	180
kips/in of sheet width	2.2	3.3	2.8	2.0	1.0
Tensile modulus					
kg/cm of sheet width	25 900	38 800	62 700	72 000	8700
kips/in of sheet width	145	220	350	400	49
Design thickness					
cm /ply	0.0111	0.0165	0.0165	0.0165	0.0118
$kips/in^2$ (Ksi)	0.0043	0.0065	0.0065	0.0065	0.0047
Tensile strength for design					
kg/cm^2	35 500	35 500	30 000	25 000	15 500
$kips/in^2 \times 10^{-3}$ (Msi)	505	505	427	355	220
Tensile modulus for design					
$kg/cm^2 \times 10^{-6}$	2.35	2.35	3.80	5.00	0.74
$kips/in^2 \times 10^{-3}$ (Msi)	33	33	54	70	10
Ultimate elongation(%)	1.5	1.5	0.8	0.5	2.1

this, it was concluded that it is possible to assume the same methodology of design calculations whether using carbon fiber sheet or steel sheet.

5.2. Improvement of fatigue strength

Road slabs are subject to cyclic loads as vehicles travel on the road. Due to this, if the slab cracks, a two-dimensional or three-dimensional displacement (i.e. rubbing between cracked planes) occurs before and after the cracking. This causes the crack to propagate, and ultimately the slab fractures under a punching shear force. The presence of water (rain water, etc.) also accelerates the deterioration of the slab as the wet concrete will gradually disintegrate.

To reinforce RC slabs, the following three methods have been established.

- Provision of additional girders.
- Bonding of steel sheet.
- Increasing the slab thickness with steel-fiber-reinforced concrete.

All of the above methods have several problems (e.g. the need to block traffic, insufficient reliability, etc.) and a new reinforcement method using new materials are required. The FORCA Tow Sheet method has attracted attention and come to be

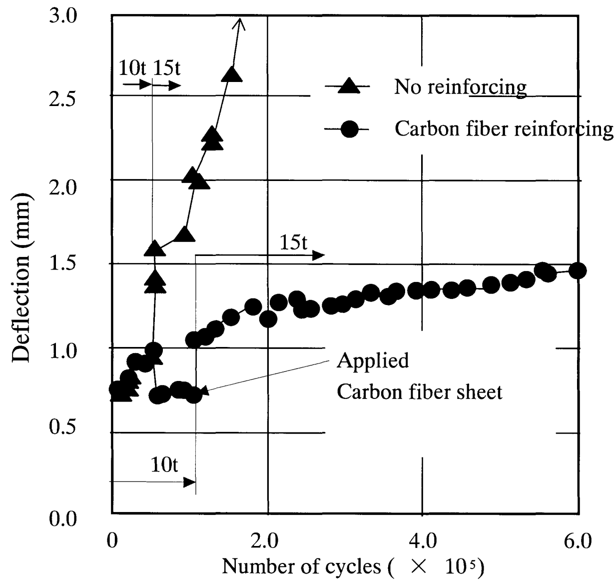

Figure 7. Fatigue test result.

used widely in this application. In this respect, credit is due largely to the following study.

Mori *et al.* [2] reported the improvement of fatigue strength of a slab through bonding a FORCA Tow Sheet to the lower surface of the slab under cyclic loading. They bonded carbon fiber sheet to the lower surface of slabs collected from an actual road bridge and then subjected the slabs to a cyclic load test using a moving wheel machine. The test load was varied between 10 tons and 18 tons. The relationship between live-load deflection at the slab center and number of load cycles has been presented in Fig. 7. The slab without carbon fiber sheet reinforcement fractured under a punching shear force after 240 000 cycles. On the other hand, a slab reinforced with two layers of carbon fiber sheet bonded to the lower surface (one layer bonded longitudinally and the other bonded transversely) showed a deflection 25% less than the reference slab for a 10-ton load, indicating an initial reinforcement effect.

After the slab was subjected to 100 000 cycles of the 10-ton load, no signs of fatigue were evident. Then, the load was increased to 15 tons with the result that the slab fatigued very slowly whilst the deflection continued to increase. However, even after 1 000 000 cycles of the 15-ton load, the carbon fiber sheets did not separate from the slab. Thus, bonding between the carbon fiber sheets and slab remained completely intact until the end of the load test. When a combination of bonding of carbon fiber sheet to the slab lower surface and addition of concrete to the slab top were used, the slab deflection decreased further and the slab fatigue was minimal. Thus, carbon fiber sheet reinforcement significantly improves the fatigue strength of a slab which is subject to a cyclic load.

6. WHY CARBON FIBER SHEET REINFORCEMENT ATTRACTS ATTENTION

Recently, the processes whereby concrete structures are damaged have been scientifically clarified. For example, corrosion, catastrophic failure, etc. of reinforced concrete has been found due to the increasing use of sea sand in place of dwindling river sand and the alkali-aggregate reaction. As a result, the importance of work management and maintenance has come to be widely recognized. The cave-in of the Oyamano Tunnel on Route 123 in Futtsu City, Chiba Prefecture during February 4th 1990 showed clearly the importance of maintaining existing concrete structures. The Hanshin-Awaji earthquake, which destroyed a large number of civil engineering and architectural structures, has also prompted widespread implementation of reinforcement for existing concrete structures.

As an effective and economical method of repairing and reinforcing concrete structures, the FORCA Tow Sheet method has gained increasing attention due to its ease of maintenance for reinforced concrete structures and its flexibility regarding applications. It is considered that the FORCA Tow Sheet method will play a vital role in the future regarding the repair and reinforcement of roads, tunnels, and other concrete structures built following the war.

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