# IN-SITU SENSING OF CARBON FIBERS IN FIBER REINFORCED POLYMER COMPOSITE TUBES FOR BENDING DETECTION

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**Keywords:** Carbon fibers, Fiber reinforced polymer composite, Self-sensing, Circular braiding, Three-point bending

**ABSTRACT**

This paper aims to investigate the sensing behaviours of carbon fibers (CFs) embedded into fiber reinforced polymer composite (FRPC) tubes during three-point bending tests via electrical resistance measurement (ERM). The FRPC tubes are fabricated by circular braiding method with Kevlar as the reinforcement fibers and vinyl ester as the resin. CFs are embedded as axial tows into FRPC tubes to serve as sensitive elements. To acquire both amplitude and direction of the bending load, CF bundles are arranged evenly around the side surface of tubes. Composite tubes are bent by a universal testing machine and the resistance changes are measured by multimeter. The experiment results show that the information of bending direction and stress amplitude can be derived from the comparation of resistance changes.

## 1 INTRODUCTION

FRPCs are widely applied for years in the aerospace, automotive, civil engineering etc. as better substitutions of alloy for their excellent mechanical properties, such as high specific stiffness and strength with low densities. However, structures made of FRPC are subjected to a variety of damages during the period of service [1]. As vital structural components, FRPCs require the in-situ assessment of loading conditions and damage distributions to prevent catastrophic failures [2]. Therefore, a number of methods have been investigated for non-destructive evaluation (NDE) of composites including X-ray, acoustic emission, ultrasound, etc. [3, 4] Unlike other NDE methods, ERM is an on-line based technology which could be performed during operation and needs no expensive device [5]. This method is dependent on the relationship between damage and resistance of CF in FRPC and various researchers have been studying on this area to analyze the process of destruction of FRPC structures.

A majority of wok about ERM in composites has been focused on the effects of different damage modes on the electrical properties of carbon fiber reinforced polymer (CFRP) composites. Joung-Man Park et al. applied ERM method on CFRP rods and found that the signal of resistance change is associated with the cracking styles of the cylindrical parts in flexural tests [6]. To monitoring the fatigue damage, Paweł Pyrzanowski et al. investigated the resistance change of CFRP beam under long-term cyclic bending loads [7]. Some other researchers have extended ERM method to composites with insulated fibers, such as Christian Viets et al. proposed a method to map the damage on glass fibre reinforced polymer (GFRP) plate with electrode grids [8].

The goal of the present work is to assess the deformation state in the FRPC tube by monitoring the resistance change of CFs, which are served as axial tows around the tube. The compression or elongation in the composites only changes the resistance of the CF in its affected area and with the comparison of all the data from every CF, the information of bending direction and force amplitude can be derived according to the deformation of tube structure under a flexural test. This approach proposed by the paper is validated through both simulations and experiments, and the analysis of the data is also a key task of this research.

## 2 SPECIMEN PREPARATIONS

In this paper, the specimen is made of FRPC as a tube, which is fabricated by circular braiding method. The inner diameter of the tube is 18mm and the outer one is 24mm, and the length is around 250mm.

### 2.1 Materials

The reinforcement fiber used for braiding is Kevlar-29 (Type 950) of which the elongation at break is over 3.7%. This property grants the composites better flexibility to bear more deformation under bending test at the cost of lowing the strength. To monitor the deformation and damage in composite, CF bundles (T700-12K, Toray, Japan) are braided into the fabric as axial tows. After fabricated by circular braiding method, the fabric is solidified with adding vinyl ester (RF 1001, Sino Composite, China) as resin through Vacuum Assisted Resin Transfer Molding (VARTM) process.

### 2.2 FRPC Tube Preparations

A specially designed circular braiding machine as shown in Fig.1 is used in this work to produce fabrics over a cylindrical metal mandrel. In this process, 24 tows of Kevlar (as 12 wrap yarns and 12 weft yarns separately) are woven with braiding angle (i.e. the angle between the braiding yarn and the axial direction of the mandrel) of 60° as well as four bundles of CFs are evenly distributed around the fabric as axial tows. The braiding angle $\alpha$ is guaranteed by adjusting parameters according to the following equations,

$$\alpha = tan\frac{\omega R}{V} \tag{1}$$

where $\omega$ is the rotation speed of the spools, $R$ is the radius of the mandrel and $V$ is the take-up speed which controls the axial motion of mandrel. However, the beginning part of the braiding tube is unstable due to an imbalance between the rates at which yarn was released from the spools and deposited on the mandrel. Therefore, the first 250mm-long of tube is abandoned to make sure a uniform structure in the rest part.

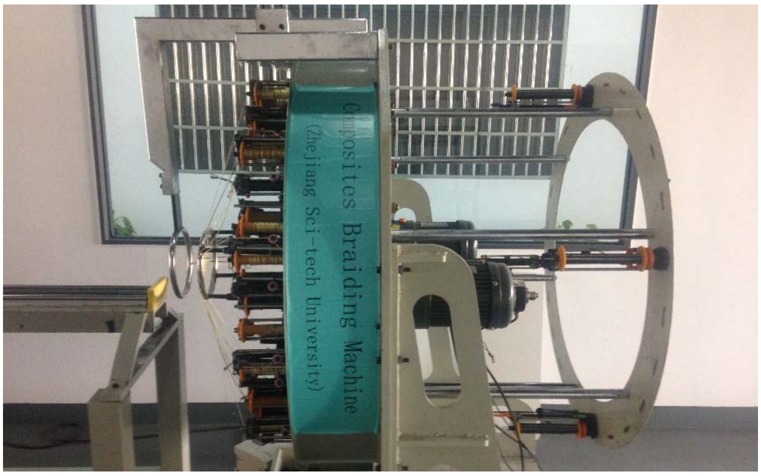


Figure 1: The  circular braiding machine with 4 carriers of axial tows

To produce electrodes on CF, the most popular way is using conductive silver adhesives to connect wire to CF after the FRPC is fabricated. This method will cause two problem: a complicated process is necessary to remove the solid resin and the exposed connection is fragile [9] for in-situ measurement when the composite is in practical working condition [10]. In the paper, Cu wires are directly connected to CF right after the braided tube is made and then the fabric is solidified by means of VARTM with the wires stretching out from the mold. The distance between two electrodes in one CF bundle is set at 200mm (Fig.2).

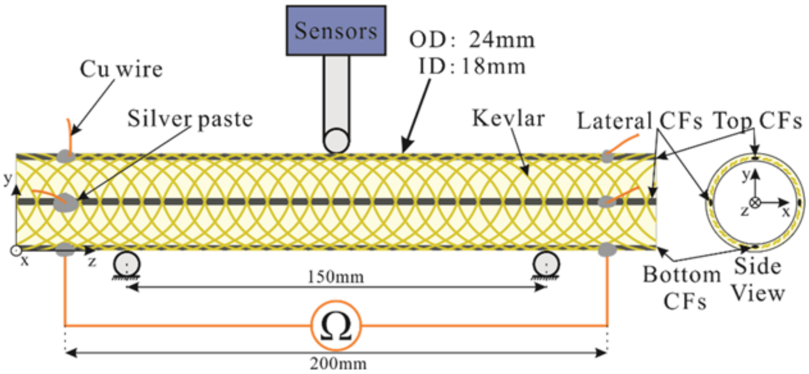


Figure 2: The structure of FPRC tube and electrical resistance method concept during 3-point bending test

After being cured at room temperature for 12 hours, the FRPC tube is extracted from the mold and mandrel, and cut into 250mm-long specimens, which are ready for 3-point bending test.

## 3 EXPERIMENTS AND RESULTS

3-point bending tests are carried out on all the specimens at a fixed indentation speed with various depth and cycles. The data of ERM of all CF bundles is collected and analyzed by comparison with strain-stress curves.

### 3.1 Experimental Setup

The bending tests are performed by a universal test machine (UTM, XBD4000G, Xinbiao, China) equipped with a 100kN load cell as shown in Fig.3. The span between the two supportive points is 150mm, whereas the resistance of each CF with an effective length of 200mm is investigated by a multi-meter (KEITHLEY 2110, Tektronix, USA).

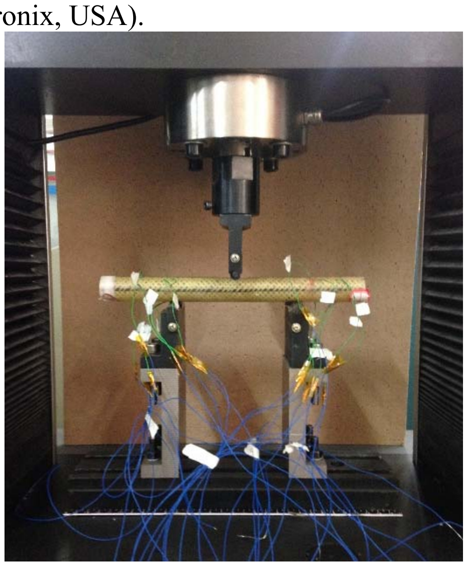

Figure 3: The photo of the UTM with specimen for 3-point bending test

The aim of the experiments is to study the relationship between the bending deformation and the resistance changes of all CFs on the tube. The indention speed and depth should be kept at a relatively low range in which the damage of composite is in or before the beginning stage. Therefore, the experiments were carried out on the prepared specimens with varying strokes from 0.5mm to 4mm and stable indentation speed of 2mm/min. The minimum stroke is to validate the sensitivity of CFs and the maximum value is chosen to moderate the fracture, which makes the resistance change unrepeatable. It should be demonstrated that the resistance change in fracture process is very important to damage detection and is studied intensively; however, this paper is focused on the process before the fracture occurs. All data from the UTM and the multi-meter are recorded in computer for analysis.

### 3.2 Comparison of Results

One of the typical result is drawn in Fig.4 and the stroke is 4mm for five circles. The resistance of the top CF bundle decreases whereas that of the bottom increases during the bending process as mentioned before. The combination of the two resistance change curves indicates that the bending indenter is applied on topside of the FPRC tube. The result shows that the top CFs are compressed in longitude and the resistance changes proportionately with the indentation depth, while the bottom CFs are elongated and the resistance increases linearly under small indentation and then a stable period will follow when the indentation exceeds a limit. This phenomenon is also been observed in other experiments and the relations between the resistance change ratio and the bending force are drawn in Fig.5 with respect to different strokes.

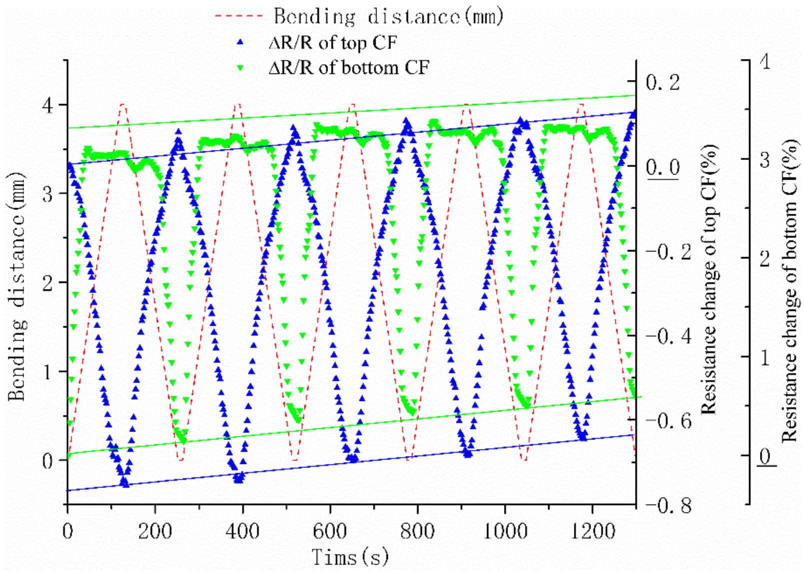


Figure 4: Resistance changes of the top and bottom CFs under 5 circles of bending

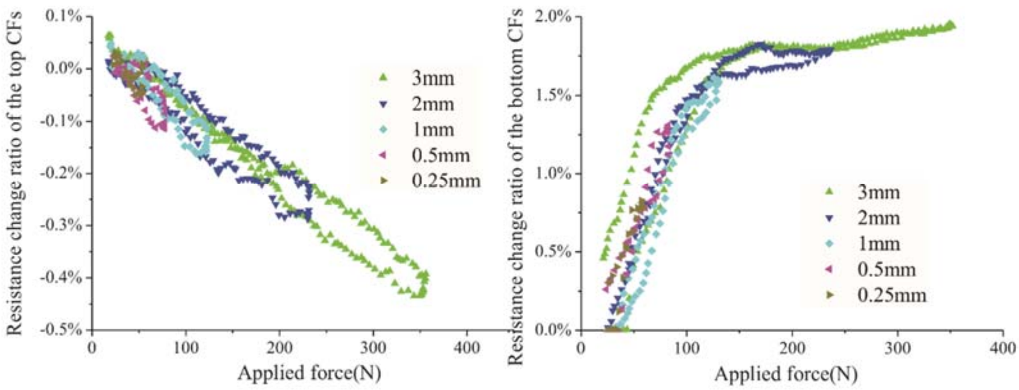


Figure 5: Resistance change ratio of CF bundle (left: top; right: bottom) under bending tests with 1 circle of different strokes

There are two things about this phenomenon should be explained. First one is about the stable period of the bottom CF bundle. This occurs when the bending force is too large and mitigates when the stroke decreases as shown in the right of Fig.5. It should be noticed that the resistance change ratio is much larger than that of top CFs and also larger than some other reports about linear strain sensing [11]. Therefore, the stable period might be caused by over-stretched which breaks the CFs severely. When the bending amplitude is large enough, the break ends will separate from each other which makes the resistance measured mainly depend on the resistance between fibers and this resistance changes less when CFs are stretched. When the indenter retrieves, the break ends will touch again which makes the linear behavior come back. A photo of the bottom side of the FPRC tube after experiment are shown in Fig.6 and two symmetrical cracks that cut the CF bundle can be clearly observed.

The other thing is about the slow increasing trend of the CF bundles. As indicated by the two pairs of color lines in Fig.4, both resistances of the top and bottom CF bundles stay a little larger after each loading circle. Fig.7 shows the relation between the resistance change ratio and bending force for over 20 circles with a stroke of 4mm. The increasing of the resistance is obviously and this trend reduces the accuracy of ERM. There might be two reasons causing this phenomenon. One reason is that the connection between Cu wire and CF bundles is made by silver paste and it will loose gradually when CF bundle is stretched and compressed which could increase the overall resistance. The other one is that some CFs in tube will break even under small bending amplitude for their unevenly twisted structure in resin and this kind of break will accumulate and make the resistance continually increase.

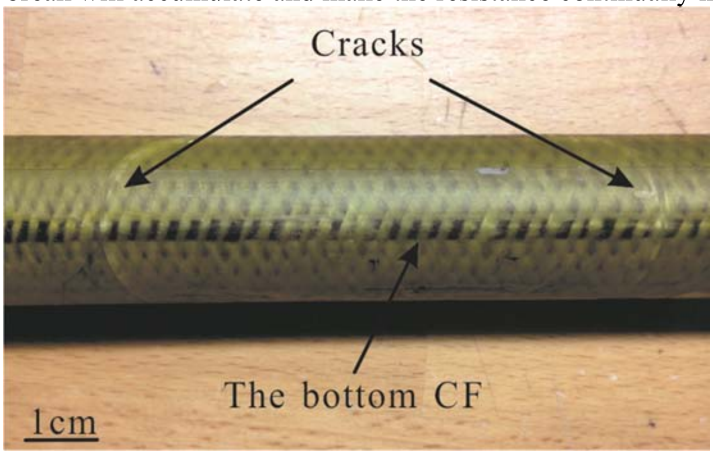

Figure 6: The photo of the cracks that break the bottom CF bundle

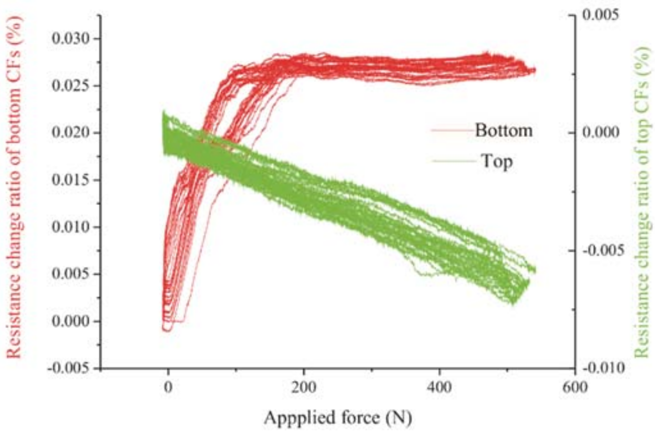

Figure 7: Resistance change ratio of both top and bottom CF bundle for over 20 circles

## 4 DISCUSSIONS

The resistance change of a single CF can be described in following equation [12]:

$$\left(\frac{\Delta R}{R}\right) = \int_0^L k_l \varepsilon_l dz + \int_0^L k_t \varepsilon_t dz \qquad (2)$$

where the longitude strain sensitivity ($k_l$) is over 4 times to the transverse ($k_t$). Although the electrical mechanism in CF bundles is much more complicate than that in a single fiber [13], this equation is still effective to predict the trend of the electrical behavior. Therefore, the main factor for the resistance change of CF in FRPC tube is the strain in axial direction and the influences caused from other direction can be ignore to simplify the following analysis process.

In FEM of the bending process by ABAQUS, the strain in Z direction of this FPRC tube is analyzed. Fig.8 shows 3 pairs of the strain of inside and outside of the tube in center of top, lateral and bottom area (as shown in Fig.2). The pairs from lateral and bottom area are all positive which means the CFs there are mainly stretched, whereas the other one has two different trends which makes the resistance of CFs in different depth change differently. This difference is the basis of the method proposed by this work that could measure the bending force and direction with the arrangement of CF bundles in CFRP tubes as in Fig.2.

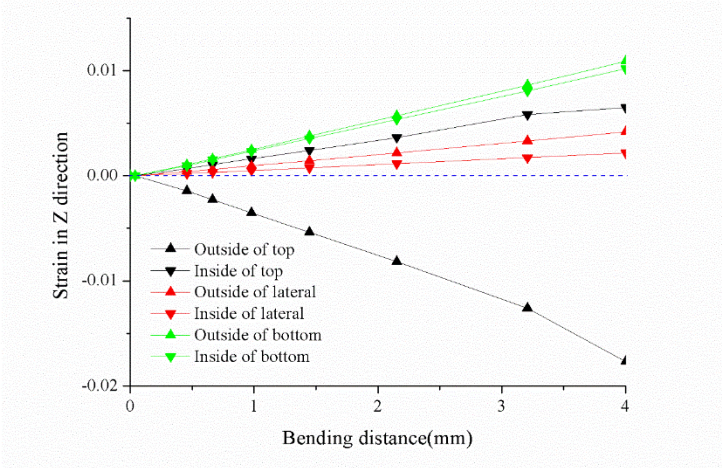


Figure 8: The different trends of the strain in different areas of the tube in bending process

Although the results of simulation agree with these of experiment, the application of this method in practical field is still a challenge. Firstly, the cracking caused by the long-term bending process is irreparable, and the CF bundle in these area will continually increase, hence how to compensate this error is a problem. Secondly, the connection of signal wire is too fragile and indention force may break it if the contact area is close enough to electrodes. Lastly, this work only has investigated the situation that the loading area is right on the center of a CF bundle, therefore comprehensive experiments should be carried out to validate this ERM method on FRPC tubes.

## 5 CONCLUSIONS

This study demonstrates an ERM method and its potential for bending detection for FPRC tube with the help of self-sensing ability of the CFs. Four CF bundles are arranged evenly around the tube as axial tows and the bundle under bending indenter will be compressed and its resistance will decrease linearly with the increasing of bending force, whereas the bundle in bottom side will be stretched and its resistance will increases when the applied force is not large. This phenomenon grant a possibility to detect the information of both amplitude and direction about the bending force in the flexural test. The experimental results have validated this method when the applied force is right on one of the axial tows, and also shown that the resistances are slowly increasing due to accumulation of tiny cracks caused by fatigue of composites.

Future work will be focused on the bending test with arbitrary direction; in order to obtain more information from ERM, more CF bundles, such as 8 or 16 axial tows, will be woven into the braided fabric.

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