A STUDY ON ELECTRICAL PROPERTY AND FATIGUE LIFE OF CARBON FIBER REINFORCED CONCRETE

Hong-zhe Dai¹ and Wei Wang¹ and Si-gang Wu²

ABSTRACT

This paper tests and analyses three point bending specimen in order to realize electrical property and fatigue life of carbon fiber reinforced concrete (CFRC) under cyclic flexural loading. The test results show that the process of fatigue deformation, for CFRC with different strength grades, is similar to that of plain concrete. Fatigue damage occurs as load cycling progresses, which indicates that the greater the stress ratio, the faster the strain develops and the greater the electrical resistance fluctuates increases. The occurrence of electrical resistance is attributed to the damage of the conductive network. This mechanism formed in this study provides a means for CFRC to monitor its extent of fatigue damage and predict its fatigue life.

Keywords: CFRC, Fatigue life, Electrical property

INTRODUCTION

Carbon fiber cement composite is a type of not only structural material but also functional material, which has drawn much attention in recent years (Bonter, et al., 2000; Chen, 1993,1996,1997; Fu, et al., 1998; Shi and Chung, 1999; Wen and Chung, 1999). There are many reasons behind this increasing interest. Cement-reinforced with carbon fibers is attractive due to its high flexural strength and toughness and low drying shrinkage, in addition to its electrical properties such as voltage-sensitive effect, seebeck effect and so on. (Chung 2000) has made a substantial review and generalization on it. However, most research work to date has been related to carbon fiber reinforced mortar (CFRM), and not to carbon fiber reinforced concrete (CFRC). Concrete differs from mortar as concrete contains coarse aggregate, and this makes concrete as structural material more than mortar.

The addition of coarse aggregate increases both the heterogeneity of CFRM and the uncertainty of its electric property. Therefore, this work is focused on damage monitoring of concrete, not mortar. The primary advantage in using CFRC is its ability sensing damage. In most cases, concrete elements work with various types of cracks. But for some infrastructures such as dams, highways and nuclear plants, high demand is to control their cracks. CFRC can monitor both crack and damage through electric resistance measurement and there is no need to embed other sensors in the concrete.

An amount of research has contributed in analyzing the fatigue behavior of plain concrete in recent years, particularly in self-monitoring of fatigue damage in carbon fiber cement composite during dynamic compression (Fu and Chung, 1996). However, fatigue behavior of CFRC has not been paid much attention by researchers, and the relationship between electrical property and fatigue behavior

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has not been studied. Therefore, this study focuses on these two issues and the achieved results are introduced in the following sections.

**EXPERIMENTAL MODEL AND METHOD**

**Materials and mix proportions**

Short carbon fibers with the length of 5 mm (Taiwan Taisu Ltd. Co.) are derived from PAN precursor. The properties of the fiber are listed in Table 1. No disperser was used because the fiber is water-miscible. Portland Cement 32.5R (made in Harbin Cement Co.) was used for all the mixtures. The fine aggregate is natural sand with maximum particle size of 4.5mm and the coarse aggregate is natural stone with particle size between 5 and 31.5 mm. The water reducing agent (WRA) and fly ash were used for C50 and C60 concrete. The mix proportions of different strength grades for CFRC specimens are shown in Table 2.

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<th>Table 1 The properties of carbon fiber</th>
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<th>Table 2 The mix proportions of the specimens</th>
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<td>Strength grade</td>
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**Procedure of making specimens**

At least twelve specimens were made for each mixture in the test. The manufacturing procedure for each CFRC mixture was:

1. The carbon fiber is manually mixed with one-third of the required water for about 2 mins;
2. The cement is then mixed with the mixture in the first step for another 2 mins;
3. The fine and coarse aggregate is added into the formed mixture with the remaining 2/3 of water and stirred using the flat beater in the concrete mixer for a further 5 mins.
4. The mixture is poured into the oiled molds (100×100×400mm), and a vibrator is then used to decrease the amount of air bubbles. Before casting the specimens, two electrodes made of copper-plated iron grids with the 10mm interval are embedded in the span centre of the specimen in parallel. The size of each electrode is 90×90mm and the distance between them is 10cm. The electrodes are used to measure the electric resistance and the fractional change in the test.
5. The specimens are demolded after 1 day, and then cured in a moist room (relative humidity is more than 97%) for 28 days.
Loading and measurement items

The three point bending beams were used for all the tests. The direction of the loading and electrodes are shown in Fig. 1. All of the flexural fatigue tests under load control were performed using a hydraulic mechanical testing system (MTS) with a 10-kN capacity. The tests were controlled by a constant load rate of 10N/s using a form of sinusoidal wave (0.1 and 10Hz). The following stress ratios s selected in the test are: 0.80, 0.85, 0.90 and 0.95 for each CFRC mixture.

Fig 1. Direction of the loading and electrodes.

The items measured in this experimental study include:

1. The deflection at the center of the beam was measured using the linear variable displacement transducer (LVDT) set between the platens.

2. The strain at the bottom side of the specimen was measured using two strain gages attached to the bottom side respectively. The strain gage was parallel to the longitudinal axis of the specimen.

3. Electric resistance measurement was made by means of the principle of Wheatstone bridge. A QJ-23 electric bridge was used to measure the initial electric resistance of the specimen. The other electric bridge connected with data acquisition and processing system was used to measure the fractional change in electric resistance. Let the resistance of three brachium pontis equal to the initial resistance of the specimen, and the change in resistance can be obtained by measuring the resistance of the forth brachium pontis.

The electric resistance, load, strain and displacement data were simultaneously collected using a computer with a “Beijing Bopu” data acquisition and processing system.

EXPERIMENTAL RESULTS AND ANALYSIS

The similar results for both 0.1 and 10Hz were obtained on different strength grades of CFRC. Because the data include much noise at higher frequency, the results with a frequency of 0.1Hz and for C40 specimens are shown as follows.

Fatigue deformation behavior

The deformation of brittle material with the number of cycles usually exhibits three stages as shown in Fig. 2:

I. The stage of damage nucleation;

II. The stage of stable damage expansion;

III. The stage of unstable damage development.
The cycle ratios corresponding to the ends of the first stage and the second stage are \( k_1 \) and \( k_2 \) respectively. For plain concrete, \( k_1 \) and \( k_2 \) is about 0.1 and 0.9 respectively, and the second stage where the strain stably expands is about 80% of the whole life. Not much can be done in a practical way to control the first and third stages of the failure mechanism, but there is the possibility of retarding or inhibiting the grows of the flaws in the second stage by using closely spaced and randomly dispersed fibers as reinforcement in the concrete.

The strain-cycle ratio curve of CFRC for different stress level under cyclic flexural loading is plotted in Fig. 3. It is clear that the strain-cycle ratio curve of CFRC is similar to that of plain concrete, the fatigue deformation of CFRC also shows the feature of three stages with the growth of fatigue life, and \( k_1 \) and \( k_2 \) are also constant. Also, the deformation process curves of CFRC have similar shape at the different stress levels.

When compared with plain concrete, \( k_2 \) of CFRC is almost constant and it is more than 0.9. This is attributed to the addition of the carbon fiber because the fiber can retard the expansion of the flaws effectively. Hence, the duration of the second stage is a bit longer than that of the plain concrete, and the higher the fiber content, the larger the counts of cycles to failure. This is the same as the effect reported in (Deng, 2005). The above test results have led to a conclusion that carbon fiber has a beneficial effect on the fatigue behavior of concrete, and the addition of carbon fiber improves the cracking resistance capacity and retard the stable growth of the concrete damage.

**Electrical property under cyclic flexural loading**

Similar results are obtained at different stress ratio \( s \). The results for \( s = 0.95 \) are shown in Fig. 4. The figure gives the fractional change in electric resistance during cyclic flexural loading at a stress amplitude equal to 0.95 of the fracture stress. Fig. 4(a) and (b) give the curves of fractional change in electric resistance -time during the first 5 cycles and the last 6 cycles before fracture in the total 72
cycles. Fractional change in electric resistance increases upon loading and decreases during unloading in each cycle. It is also can be seen that fractional change in electric resistance of the specimen increases gradually from 0.5% to 12% as load cycling progresses before fracture. When the fracture occurs, fractional change in electric resistance abruptly and greatly increases.

Fig 4. Fractional change in electric resistance during repeated flexural loading at s=0.95. (a) First 5 cycles. (b) Last 6 cycles

The above phenomena can be explained in terms of the damage of the conductive network model. The conductivity of CFRC includes ionic conductivity, hole conductivity, and electronic conductivity. According to (Sun et al., 1998), when the carbon fiber content is high, electronic conduction and hole conduction play a main role in this conduction model of CFRC. When the flexural load is applied, the inherent flaws develop and new microcracks emerge within the specimen. This damage weakens the ability for electron and positive hole of carbon fibers to transfer, and causes an increase in interval potential barrier between carbon fibers. Hence, the conductive network shows a tendency to be destroyed and causes fractional change in electric resistance to increase. Upon subsequent unloading, the developing microcracks trend to close, the interval potential barrier between carbon fibers decreases, and the probability for electron and hole to transfer increases. The conductive network shows a tendency to recovery and the resistance decreases. While the fracture occurs at the 72nd cycle, a sufficient number of unstable cracks join to form a continuous crack and the failure of the specimen follows immediately. The conductive network is severely destroyed, which causes the electric resistance to considerably increase at the moment.

However, it has been observed that the fractional change in electric resistance of most specimens is less than 0.1 before fracture. The electric resistance shows a slight but consistent increase along with repeated cycles and this indicates the occurrence of slight damage. For this reason, this slight increase in electric resistance could be seemed as a warning limit of the impending fracture. While the fracture occurs, that is, fatigue failure, fractional change in electric resistance greatly increased, obviously due to cracking.

**Relationship between residual resistance and fatigue life**

Curves of fractional change in electric resistance -cycle ratio under different stress ratio are plotted in Fig. 5. Fig. 5(a) and (b) show the relationship between fractional change in electric resistance and the cycle ratio (fatigue life) before fracture and until fracture respectively. In contrast to Fig. 3, it can be found that the shape of the fractional change in electric resistance -cycle ratio curve is similar to that of strain-cycle ratio curve. Therefore, the strain/stress condition can be also obtained through electric resistance measurement during cyclic loading.

It can be observed that fractional change in electric resistance irreversibly increases with the growth of fatigue life, and it does not return to zero at the end of each loading cycle. This irreversibly increased electric resistance is called the residual resistance which is attributed to the damage of conductive network. However, the relationship between the residual resistance and the cycle ratio varies with the
stress amplitude under the cyclic loading. The greater the stress ratio, the greater the residual resistance increases.

![Fractional change in resistance vs. cycle ratio under different stress ratio](image)

Fig 5. Fractional change in electric resistance vs. cycle ratio under different stress ratio (a) before fracture; (b) until fracture.

With high stress amplitude such as 95% of the fracture stress, the electric resistance has a net increase after the first few cycles. Fractional change in electric resistance reaches 1% and 14% when the cycle ratio is equal to 0.1 and 0.95 before fracture respectively. This provides a warning limit for CFRC’s failure adjustment. As the stress level decreases (e.g. 80% of the fracture stress), fractional change in electric resistance almost remains zero in the early stage of fatigue life, indicating that the residual resistance is small. But with the growth of fatigue life, the residual resistance is negligible, indicating the occurrence of the slight damage which hindered the transferal of the electron and positive hole. The residual resistance is monotonic but not linear with the fatigue life, and the slight increase of residual resistance provides an indication of the extent of damage in the regime of slight damage.

In contrast to Fig. 3, the fractional change in electric resistance can also demonstrate the damage of the specimen. The damage is partially reversible, as indicated by the partially reversible increase in electric resistance. In contrast, the strain is indicated by a reversible increase in electric resistance. The greater the stress amplitude, the faster the strain develops, the greater the damage, the greater the residual resistance irreversibly increases. At low stress level, the residual resistance increases slightly and irreversibly with the growth of fatigue life. This is the same as the strain development. Therefore, the residual resistance in the regime of major damage provides a means for CFRC to monitor its extent of fatigue damage.

**CONCLUSIONS**

CFRC exhibits the same fatigue deformation behavior as plain concrete, that is, their deformation develops through three stages with the growth of fatigue life. However, carbon fiber improves the cracking resistance and has a beneficial effect on the fatigue behavior of concrete. The damage condition in CFRC can be monitored by measuring electric resistance. Residual resistance occurs as load cycling progressed, the greater the stress ratio, the faster the strain develops, the greater the residual resistance irreversibly increases. This mechanism formed in this study provides a means for CFRC to monitor its extent of fatigue damage, as different strength grades of CFRC are similar in their electrical property and fatigue behavior.

**REFERENCES**


