Electro-Mechanical Impedance (EMI) based Axial Loads Influence on Damage of Steel Fiber Concrete

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Abstract
Steel fiber concrete has higher tensile strength, higher fatigue strength and higher fracture toughness than traditional reinforced concrete. Because of these advantages, it is one of the most widely used types of material in water resources and hydropower engineering. In this paper, the Smart Aggregate (SA) sensors which made by sandwiched the water proofed piezoceramic patch into protective materials were casted into the steel fiber concrete specimens. The steel fiber concrete, which average compressive strength is 50 MPa, are divided into five groups according to different content of steel fiber (0, 30, 60, 90, 120) (kg/m³). Based on the electro-mechanical impedance signal which acquired from the Smart Aggregate (SA), the cracks and the damage status of steel fiber concrete can be detected. Specifically, the effects of axial compressive load were investigated by using step-by-step loading scheme which includes elastic, plastic and the destruction loading stage. A normalized Root-Mean-Square Deviation (RMSD) based analysis was developed to determine the relationship between destruction and impedance signal. The test results show that the normalized RMSD impedance damage index increases gradually with the increase of axial loading. It can be used to monitor the damage status of steel fiber concrete.

Keywords: Health monitoring; Steel fiber concrete; Axial loads; Impedance method; Smart aggregate

Introduction
In recent years, steel fiber concrete has been widely used in high-rise buildings, long-span bridges and hydropower structures [1], because of its improved properties in tensile strength, fatigue strength and fracture toughness [2,3]. Therefore, the entire service period structural health monitoring of steel fiber concrete structures become much more important. The application of high-performance intelligent material sensors in damage detection has become the trend of structural health monitoring. Among them, smart aggregate as the representative for smart materials have been widely used in structural damage detection for its good mechanical and electrical coupling properties. During past few years, the electro-mechanical impedance technique has become a new promising method in crack detection and structure health monitoring and it has been widely used in aerospace and aircraft structures [4-6], civil engineering [7] and so on.

Song et al. [8] proposed the concept of embeddable piezoceramic based “smart aggregate” for health monitoring of concrete structures. Initially, Gu et al. [9] applied smart aggregate to the early strength monitoring of concrete. By establishing the empirical relationship between the amplitude of the signal received by the sensor and the experimental strength of the concrete, the early compressive strength of the concrete was effectively predicted. Song et al. [10] applied smart aggregate to detect an over-height truck collision with a concrete bridge. The smart aggregates also have been used to identify internal cracks effectively in reinforced concrete structures by using the active sensing [11]. Experiments show that the wavelet packet analysis method can effectively identify the development of concrete cracks. And then, the feasibility of using smart aggregate to monitor the internal stress of a structure was verified by Du et al. [12].

Electro-mechanical impedance method, which originated in the 1990s, is a novel health monitoring technology which can detect the internal damage of the structure by analyzing the structural vibration characteristics. In 1993, Liang et al. [13] first proposed the electro-
mechanical impedance method for structures with a piezoceramic transducer. After that, Liang et al. [14] used EMI to study actuator power consumption and system energy transfer. Later Liang et al. [15] researched the structure-PZT coupling resistance through experiments and derived a simple PZT-driven coupling admittance expression.

Soh et al. [16] have done a great deal of experimental research on micro-damage detection in civil engineering structures and found that non-parametric index using Root-Mean-Square Deviation (RMSD) correlated well with the damage progression in the structure. Since then Soh and Bhalla [17] have also developed a fuzzy conceptual model that can quantitatively demonstrate the degree of damage in concrete by using the amplitude of change of structural equivalent stiffness. In addition, Annamdas and Soh [18] present a new embedded PZT patch and have done a great deal of experimental research on micro-damage detection in civil engineering structures and found that the micro-cracks of concrete structure can be detected by using electro-mechanical impedance method. After that, Lim et al. [19] proposed a new method for damage diagnosis from the measured admittance signatures in terms of equivalent structural parameters. Then Bhalla and Soh [20] present a new method of damage diagnosis by changing the structural impedance signal at high frequencies using PZT patches. Tseng and Naidu [21] used some simple structures to find the impedance relationship between the PZT and the structure, and confirmed the feasibility of the electro-mechanical impedance approach. The feasibility of using impedance-based non-destructive testing to identify damage in concrete was also verified [22]. Based on
smart Piezoelectric Transducer (PZT) patches, Tseng and Wang [23] further developed a modeling framework to determine the structural impedance response and the dynamic output forces of PZT patches from the electric admittance measurements. Park et al. [24] obtained plenty of results by using PZT sensors to monitor the mechanical properties of concrete structures. They found that electro-mechanical impedance methods can be used to identify the degree of structural damage in harsh environments and the sensitivity of electro-mechanical impedance based micro-damage monitoring have been verified [25]. In order to remove the effects of temperature factor from the changes of PZT impedance signals caused by structural damage, Park et al. [26,27] designed an algorithm that incorporated temperature compensation into the piezoelectric impedance approach to assure its practical application.

Furthermore, Dumoulin et al. [28] used SAs to investigate and compare different damage indicators in a reinforced concrete beam subjected to three-point bending test. Karaiskos et al. [29] also focused on ultrasonic wave propagation techniques by using embedded piezoelectric transducers for online monitoring of concrete and demonstrated the performance of the system which is able to detect the cracking until complete failure.

In addition, Ayres et al. [30] addressed electro-mechanical impedance measurements from experimental structures and a subsequent statistical method for quantitatively determining the classification of “damaged”. A potentially powerful tool for damage detection and health monitoring named E/M impedance technique was demonstrated by Giurgiutiu et al. [31]. Yang et al. [32] employed smart Optical Fiber Sensor (OFS) and lead zirconate titanate (PZT) impedance sensor for comprehensive health monitoring of rocks. Yang et al. [33] developed a reusable PZT transducer setup for monitoring the initial hydration of concrete and structural health monitoring. The feasibility of the EMI sensing technique for the real time strength development of early-age concrete was investigated by Shin and Oh [34]. Park et al. [35] explored the capability of the E/M impedance status monitoring of pipeline structure after earthquake. Park et al. [36] summarized the hardware and software issues of impedance-based structural health monitoring based on piezoelectric materials. Park et al. [37] developed an EMI based SHM approach using modified auto-regressive model with exogenous inputs (ARX). Wang et al. [38] extended the impedance method to timber specimens for damage detection. All of these researches demonstrated that the electro-mechanical impedance approach is a promising way to monitor the healthy state of structures.

In our previous studies, the influence of axial force on properties of steel fiber reinforced concrete in elastic stage was investigated [39]. Experimental results demonstrated that the axial load has a great influence on EMI value, and further, there is a great linearity between the normalized-RMSD and the applied loading, shown in Figure 1. According to the axial forces influence of steel fiber concrete within the elastic range of strains, further investigation about the ultimate load influence was carried out in this paper. The E/M impedance method was used to detect the damage status of steel fiber concrete. Step-by-step loading case was conducted, which can clearly show the axial loading effect during elastic, plastic and the destruction stage of steel fiber concrete. The normalized RMSD-based analysis
which proposed in the earlier paper of elastic range of strains was also applied. The test results show that the normalized RMSD was gradually increased with the increase of axial load. The normalized RMSD-based index is effect to monitor the damage status of steel fiber concrete.

Piezoceramic Based Smart Aggregate (SA)

Smart aggregate is a kind of PZT based sensor which made by sandwiched the waterproofed PZT into the marble protection. Because of the piezoelectric properties [40], smart aggregates can be used as sensor in this experiment. Figure 2(a) shows the detail information about smart aggregate. A fragile PZT connected with lead wire was embedded in the center of the marble protection to prevent sudden damage. The dimension of the PZT (D33) is 15 mm × 15 mm square. The diameter of the smart aggregate is 25 mm, and the height is 20 mm. Figure 2(b) shows a photo of a fabricated smart aggregate and an exploded view of it. Smart aggregates have been used in concrete structure health monitoring research; for example, Yan et al. [41] applied smart aggregates to the damage monitoring of the shear wall under repeated load and found that the smart aggregate can determine the damage area of the shear wall.

Electro-Mechanical (E/M) Impedance and Normalized Root-Mean-Square-Deviation (RMSD) Approach

Electro-mechanical impedance method, which diagnoses damage by comparing the E/M impedance of smart aggregates before and after damage happens, is a promising new technique for damage detection [42]. In this paper, the SA was casted into the center of concrete specimen, once the damage occurred, the natural frequencies of the whole structure changes, thereby further causing the change of E/M impedance [43,44]. Therefore, the E/M impedance signal measured by the smart aggregates can be used to diagnosis and detect the damage status of structure. In addition, it can further perform the damage diagnosis and the health monitoring on various structures. In electronic electrodynamics, admittance is defined as the reciprocal of impedance. The formula of admittance, which is shown in Equation (1), can be derived according to the equilibrium equation, the piezoelectric equation and the wave equation [45]. Equation (2) shows the formula of impedance derived from the formula of admittance.

\[ Y = \frac{w_A}{i} \left( \frac{Z_{33}}{Z_A} - \frac{Z_s}{Z_s + Z_A} d_{33} \frac{1}{Y_{22}} \right) \]  
\[ Z(\omega) = \frac{1}{Y} = \frac{h_A}{i\omega} \left( \frac{Z_{33}}{Z_A} - \frac{Z_s}{Z_s + Z_A} d_{33} \frac{1}{Y_{22}} \right)^{-1} \]  

where, Y is admittance, \( \omega \) is the angular frequency of excitation. \( i \) is imaginary unit. \( w_A, h_A, l_A \) are respectively the PZT’s width, thickness and length. \( Z_{33} \) is the complex permittivity when PZT’s stress is zero or a constant. \( d_{33} \) is piezoelectric constant and \( Y_{22} \) is complex Young’s modulus at zero or constant electric field. \( Z_s \) and \( Z_A \) are representing PZT’s mechanical impedance and structure’s mechanical impedance respectively.

A normalized RMSD-based analysis is developed to process the impedance signal. RMSD has been widely used in data processing. The basic idea of RMSD (Root-Mean-Square Deviation) is to compare the arithmetic square root under different status of the same data with each other. By using RMSD, the structural information in different status is compared to the information in the non-destructive status to obtain the structural damage. The equation of RMSD and the equation of normalized-RMSD are shown in Equation (3) and Equation (4), respectively.

\[ RMSD = \sqrt{\sum_{i=0}^{2}(Z_i - Z_0)^2} \times 100\% \]  
\[ NRI = \frac{I_{RMSD}^1 - I_{RMSD}^0}{I_{RMSD}^1 - I_{RMSD}^{100\%}} \]  

where, \( Z_i \) is the impedance of a measuring point at a single frequency and \( Z_0 \) is the reference value of the same frequency at 100 kN. \( I_{RMSD}^0 \) is the RMSD index at initial loading condition in the experiment. \( I_{RMSD}^{100\%} \) is the RMSD index of the specimen under no-loading condition. \( I_{RMSD}^1 \) is the RMSD index with the largest load applied. Although RMSD have been employed to associate the damage level with the changes in the impedance value, it is difficult to determine the location of damage using such methods [46].

Experiment Preparation and Experimental Setup

This section describes the steel fiber concrete that will be used to demonstrate the smart aggregate based impedance method for destruction monitoring. In addition, the experimental setup involves the device we used and the loading method.

Steel fiber concrete specimen

The concrete mix proportions are shown in Table 1. Table 2 shows that steel fiber concrete specimens were divided into five groups based on the different content of steel fiber. The steel fiber we used in concrete specimen is shown in Figure 3. Every group has three specimens. All the concrete specimens are the same size, which is 150 mm × 150 mm × 150 mm. For each specimen, a smart aggregate is embedded in the center of the specimen, as shown in Figure 4. Figure 5 shows the photo of the specimen.

| Table 1: Proportions of concrete mix (kg/m³). |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cement (P042.5) | sand | stone | water | fly ash | water-reducing admixture |
| 400             | 740  | 1100  | 150  | 50  | 7.4 |

| Table 2: The groups of steel fiber concrete. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Groups          | 1st             | 2nd             | 3rd             | 4th             | 5th             |
| Specimen’s number | 1-1,1-2,1-3     | 2-1,2-2,2-3     | 3-1,3-2,3-3     | 4-1,4-2,4-3     | 5-1,5-2,5-3     |
| The content of steel fiber (kg/m³) | 0 | 30 | 60 | 90 | 120 |

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applies high frequency AC voltage to smart aggregate actuator, which causes the actuator to generate high-frequency vibration and give mechanical waves inside the structure. The sweep frequency ranges of the impedance signal 100 kHz to 500 kHz. The real parts of the E/M impedance signals were recorded to measure the influence of ultimate axial force on destruction of steel fiber concrete.

**Experiment Preparation and Experimental Setup**

**Experimental procedures**

As shown in Table 3 and 8, the process of the experiment can be divided into three phases. A teach maintaining stage, the loading level was maintained constant for 30 min. The impedance signals were measured at every beginning, midpoint and ending of the maintaining time. In the first phase, the loading speed of the specimens was 2 kN/s and the loading level was maintained constant at 100, 200, 300, 400, 500 and 600 kN. In the second phase, the load increase with a rate of 1 kN/s. The loading level maintained constant at 700, 800 and 900 kN, respectively. In the last phase, the loading speed was 0.5 kN/s until the specimen was fully damaged. The maintaining process was at integral hundreds digits.

**Table 3: Loading method of the experiment.**

<table>
<thead>
<tr>
<th>Loading range (kN)</th>
<th>0-600</th>
<th>600-900</th>
<th>900-destruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading gradient (kN)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Loading speed (kN/s)</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Loading time (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gradient loading time</td>
<td>50</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Gradient maintaining time</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
</tbody>
</table>

**Figure 11:** Electrical impedance signature of group two acquired from the SA (real part of the impedance signal). (a) 0 kN to 400 kN; (b) 500 kN to 900 kN; (c) 1000 kN to 1280 kN.

**Figure 12:** Electrical impedance signature of group three acquired from the SA (real part of the impedance signal). (a) 0 kN to 400 kN; (b) 500 kN to 900 kN; (c) 1000 kN to 1220 kN.

**Experimental results and discussion**

Figure 9 shows the picture of crashed specimen in this experiment. As shown in Figures 10-14, we can see there is no consistent relationship between force and amplitude of impedance. Although the amplitude of impedance can be considered as chaotically increasing as the force increases (group two, group four and group five) and it is hard to reach an agreement on every cases (group one and group three). As the force increases, the corresponding frequency of the amplitude of impedance also shows a chaotically trend. We cannot get an explicit relationship between the steel fiber concrete destruction process and the real part of the impedance signal. In order to show the relationship between axial load and impedance signal more clearly, the normalized RMSD index was calculated at
each measuring points, the authors draw them into a histogram, which showed in Figures 15-19.

Generally, the normalized RMSD index increase with increasing load in Figures 15-19. As aforementioned, this paper mainly focused on the plastic stage and destruction stages. Therefore, the impedance of a measuring point at 100 kN was set as a reference value. As shown in the Figure 19, the normalized RMSD started from 200 kN. In order to eliminate the random errors caused by unstable random factors, we average the RMSD of each group. And we can clearly see from the figures that the normalized RMSD index of steel fiber concrete will increase by a large margin near the time of destruction. The normalized RMSD index can be effectively used to monitor the steel fiber concrete destruction process and predict the destruction of steel fiber concrete.

With further analysis, the reasons of the date fluctuation are mainly caused by following aspects. Firstly, the stress redistribution around SA leads to irregular voltage signals due to the direct piezoelectric effect. Secondly, the SA sensors receive the acoustic signals, which caused by the opening and closure of cracks, as well as the sensing signals, which complicate the wave forms. Thirdly, the uneven distribution of the steel fibers in the steel fiber concrete makes the distribution of the cracks uneven, which result in some differences between the specimens. Fourthly, concrete vibrating leads to slight deviation of smart aggregates, thus affecting the receiving

Figure 13: Electrical impedance signature of group four acquired from the SA (real part of the impedance signal). (a) 0 kN to 400 kN; (b) 500 kN to 900 kN; (c) 1000 kN to 1160 kN.

Figure 14: Electrical impedance signature of group five acquired from the SA (real part of the impedance signal). (a) 0 kN to 400 kN; (b) 500 kN to 900 kN; (c) 1000 kN to 1200 kN.

Figure 15: The NI-RMSD index of group one.

Figure 16: The NI-RMSD index of group two.
signal amplitude.

**Conclusion**

The proposed piezoceramic based impedance method was experimentally proven to be is liable approach in health monitoring and further monitoring the damage status of steel fiber concrete. Impedance method can be used to measure the impact of axial load on the steel fiber concrete. Since smart aggregates were embedded into steel fiber concrete, the process of crack development can be monitored by using impedance method. In addition, a normalized RMSD-based analysis is developed to process the data. It can be seen that with the increase of the axial load, the normalized RMSD index is gradually increased. Therefore, the effect of axial loads on steel fiber concrete can be clearly demonstrated by normalized RMSD.

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