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Mechanical and damage sensing properties of smart high-performance fibre-reinforced concrete beams under bending

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ABSTRACT

Self-sensing high-performance fibre-reinforced concrete (SS-HPFRC) is a promising smart construction material that potentially replaces traditional sensors in structural health monitoring systems for infrastructure. This study investigated the mechanical and damage detection properties of SS-HPFRC beams containing different short smooth steel fibre contents under bending. The research simultaneously measured electrical resistance at tensile and compressive sections using wired and wireless measurements and captured video of crack propagation. The test results indicated that the damage of SS-HPFRCs could be observed in real-time by evaluating the fractional change in electrical resistance (FCR) under bending. The FCR response at the tensile section indicated that major cracks had opened and propagated, regardless of the fibre content. Additionally, increased FCR in the compressive section suggested cracks propagating from the tensile to the compressive sections. Besides, the embedded electrode direction influenced the FCR of SS-HPFRCs before a peak flexural stress. A model of a conductive network in SS-HPFRC under bending was developed to explain the FCR response. Integrating SS-HPFRCs with wireless electrical resistance measurement systems would be utilised in the SHM system to detect abnormal phenomena in structures early and provide timely repair and maintenance to prevent catastrophic collapse.

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Damage sensing; steel fibre; structural health monitoring; self-sensing high-performance concrete; wireless measurement

1. Introduction

Structural health monitoring (SHM) systems for infrastructures and high-rise buildings have recently been a concern because the catastrophic collapse of these structures has resulted in human and economic losses. One of the main reasons for structural catastrophes is the generation and opening of cracks in concrete structures without detection or warning. In the SHM system, the attached or embedded sensors were used to monitor damages/cracks in structures. However, they had low durability and should be frequently

replaced in the structural concrete life cycle, consequently causing a high cost for the SHM system [1]. In addition, the application of sensors in the SHM systems was limited to local positions. Besides, embedded sensors would decrease the strength of structures. Recently, some technologies such as acoustic emission, ultrasonic testing, and drone image analysis were utilised to detect crack positions in structures [2–4]. However, it is limited to structures at difficult access locations and requires highly strong analysis software and computers to evaluate.

Self-sensing concretes with self-sensing and high mechanical abilities have been developed to overcome the drawbacks of current sensors or image analysis in SHM systems [5–8]. Functional fillers (FFs) with high electrical conductivity such as steel fibres, carbon fibres, nickel powder, steel slag aggregates (SSAs), carbon black, graphene, and multiwall carbon nanotubes (MWCNTs) [9–18] were generally added into concretes to make self-sensing concretes (i.e. concrete can work as sensors with sensing abilities such as damage, stress, or strain sensing under external loads). The fractional change in the electrical resistance (FCR) of the FF conductive network under external loads can be used to observe stress/strain or damage in self-sensing concretes. Le et al. [19] obtained the linear correlation between FCR and stress in the elastic region and a probabilistic correlation from the elastic to the fracture region for SS-HPFRCs containing steel fibres and steel slag aggregates. Li X and Li M [20] reported an equivalent circuit model of smart concrete containing carbon black with cracks to explain the correlation between FCR (measured by an alternating current, AC) and crack generation.

To apply the SHM system with smart material for large-scale and highly important infrastructure, self-sensing high-performance fibre-reinforced concrete (SS-HPFRCs) with damage-sensing ability and high mechanical properties should be deeply investigated and developed. However, the damage-sensing ability of SS-HPFRCs under bending has little information. Le et al. [5,21,22] indicated that short steel fibre (a high electrical conductivity) was a potential FF to disperse into SS-HPFRCs because it not only improved the self-sensing ability of SS-HPFRCs but also improved their mechanical properties, such as ductility, tensile strength, and crack resistance. Le et al. [23,24] and Kim et al. [25] reported that SS-HPFRCs with 2.0 vol% short smooth steel fibres (6 mm in length) produced self-damage sensing ability under direct tension. Recently, Le et al. [5] investigated the damage-sensing ability of SS-HPFRCs under compression. However, almost all structural components worked under bending load, such as beams and slabs, not direct tension. Recently, Lai et al. [26] investigated the FCR response of SS-HPFRCs containing 2 vol% short smooth steel fibres incorporating SSAs and/or MWCNTs under-bending. They reported that the electrical resistance of SS-HPFRCs decreased as the bending stress increased to peak stress. However, the damage and damage propagation detections have not been analysed. In addition, the damage/crack propagation detection of SS-HPFRCs under bending has not been investigated. There has not been any infrastructure or high-rise buildings in the world using smart SS-HPFRCs. All research is still in the Laboratory and Pilot project because the application of the smart SS-HPFRCs to real structures requires a combination of IoT and central management, and has not a standard or code regarding smart concrete materials. Some research works have been applied to the smart concretes in the pilot project such as: Kim Dong Joo et al. [2019, 2021]

investigated the ability of smart SS-HPFRC anchorage to detect the tendon fracture in the pre-stressed concretes [27,28]. Ding S et al. [2022] [29] and Lee et al. [2020] [30] investigate the SS-HPFRCs for applying to the management of railway concrete structures. The IoT system in this study incorporating the SS-HPFRCs was investigated to produce a potential application for the SHM system of infrastructure and high-rise buildings.

This study aims to investigate the damage-sensing characteristics of SS-HPFRCs under bending. Short, smooth steel fibres were utilised as an FF to improve not only the FCR response but also the flexural strength and the crack resistance of SS-HPFRCs. The detailed objectives are 1) to investigate the mechanical properties and the FCR responses at tensile and compressive sections of SS-HPFRCs containing different contents of short smooth steel fibre under bending loads; 2) to analyse the self-damage sensing characteristics, including damage generation and propagation detection of SS-HPFRCs, and 3) to propose a conductive network model for explaining the damage sensing characteristics of SS-HPFRCs under bending.

2. Experiments

2.1. Materials and specimen preparation

Table 1 summarises the SS-HPFRC compositions based on the weight ratio of cement. The matrix compositions of SS-HPFRCs, including cement, silica fume, river sand, water, and superplasticizer, in this study were determined according to the cement weight ratio. The smart concrete has not yet been standardised or codified for mix design; therefore, the concrete mix design in this study was adopted from previous studies by authors and our research group [5,25]. The steel fibre content was varied from 0.5 to 2% by volume of the mixture to improve not only the crack resistance or the mechanical properties but also the self-sensing ability of composites. Experimental tests were conducted to understand the damage-sensing ability of SS-HPFRCs containing different short smooth steel fibre content levels under flexural loads. The notations F0, F0.5, F1, and F2 represent steel fibre volume contents of 0, 0.5, 1.0, and 2.0 vol% in SS-HPFRCs, respectively. C2 denotes two vertical pre-formed cracks in bending specimens (Table 1). The pre-formed cracks within flexural specimens are also considered to ensure crack propagation within the gauge length measurement.

Figure 1 illustrates images of the primary materials incorporated in this study. Ordinary Portland Cement (Figure 1a, the ASTM C150 Type I) and silica fume

Table 1. Matrix compositions of SS-HPFRCs by cement weight ratio.

Notation	Cement (cwr)	Silica Fume (cwr)	River Sand (cwr)	Water (cwr)	Super-plasticizer (cwr)	Fiber (vol%)	Pre-formed Crack (ea)
F0C0	1.00	0.25	1.25	0.20	0.12	–	0
F0.5C0	1.00	0.25	1.25	0.20	0.12	0.5	0
F1C0	1.00	0.25	1.25	0.20	0.12	1.0	0
F2C0	1.00	0.25	1.25	0.20	0.12	2.0	0
F1C2	1.00	0.25	1.25	0.20	0.12	1.0	2

cwr means cement weight ratio.

(Figure 1b), comprising 90% SiO₂ with an average particle size of 10 µm, were utilised as binders in each matrix. The river sand (Figure 1c) used in this study had a maximum diameter of 1.25 mm. The tap water (Figure 1d) with a water-to-cement ratio (W/C) of 0.2 was used, and the superplasticizer-based polycarboxylate (SR5000F of Silk Road, Figure 1e) was 0.12 by weight of cement. The steel fibres (Figure 1f) have a diameter of 0.2 mm, a length of 13 mm, an elastic modulus of 200 GPa, and a tensile strength of 2447 MPa.

A mixer was employed to ensure the thorough and homogeneous mixing of the materials. Initially, the binders (silica fume and cement) were mixed for about 3 minutes. River sand was added to the mixture and blended for 5 minutes. Then, the water was gradually added to the mixture and mixed thoroughly for 2 minutes. Following this, a superplasticizer was slowly incorporated and mixed continuously for an additional 2 minutes. The flow table test value of fresh mixtures was controlled from 190 to 210 mm to ensure uniform distribution of fibres in fresh mixtures. Then, steel fibres were manually incorporated into the mixture and mixed for 2 minutes.

Fresh mixtures were poured into specimen moulds. All specimens were placed on a vibration table to eliminate voids in the SS-HPFRC matrices. They were then covered with a plastic sheet to preserve the laboratory temperature at $25 \pm 2^\circ\text{C}$. After 48 hours, the specimens were demoulded and transferred to a hot water tank maintained at $80 \pm 5^\circ\text{C}$ for 72 hours.

Figure 2 shows the specimens designed for evaluating the damage sensing under bending. Bending specimens with sizes of 150x150x150 mm and 40x40x160 mm were

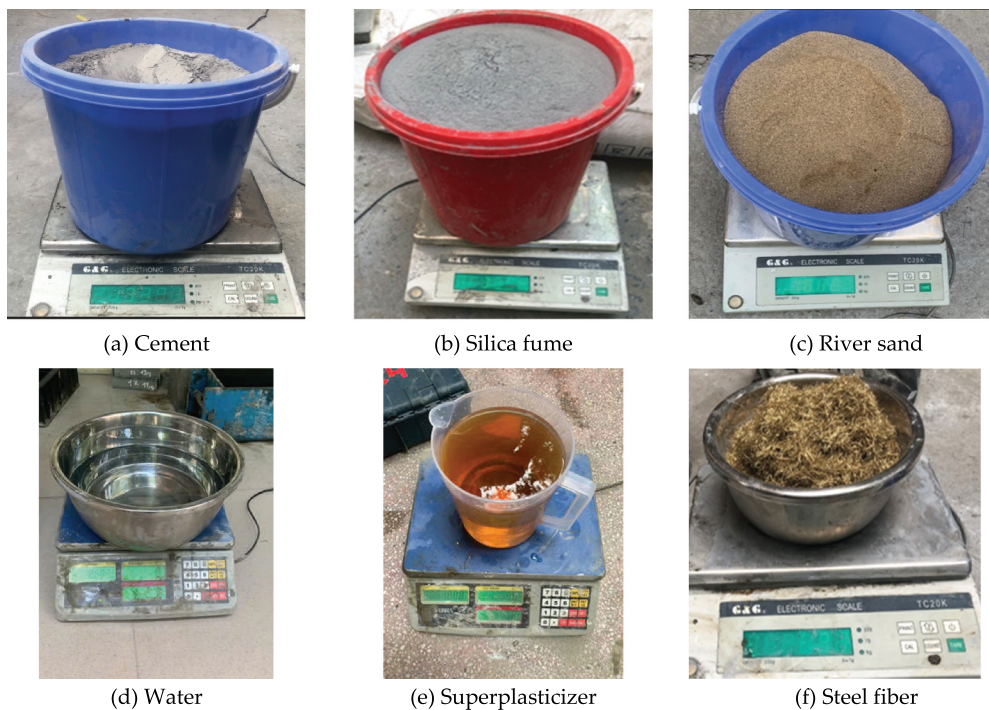


Figure 1. Images of primary materials utilized in this study.

prepared according to ASTM C293/C293 M-16 and ASTM C348 Standard, respectively. Based on the study of Lai et al. [26] and Han et al. [1], to measure the resistance during the test, embedded stainless steel wires (EW) are embedded at specific points inside the specimen. For the $150 \times 150 \times 600 \text{ mm}^3$ specimen, EW1 ($150 \times 150 \text{ mm}^2$ in width and depth and 180 mm in height) and EW2 ($150 \times 150 \text{ mm}^2$ in width and depth and 70 mm in height) were positioned within the compression and tension zones of bending specimens (Figure 2a, b). The diameter of the wire was 1 mm while the mesh size was 10 mm. Figure 2c presents the specimen geometries utilised in evaluating the effects of preformed cracks on the FCR response of SS-HPFRCs. The smooth plastic sheets with a thickness of 2 mm and a depth of 50 mm were employed to generate the notches in specimens. As can be seen in the F1C2 specimen, sheets with a width of 2 mm and a depth of 50 mm are located within the gauge length (Figure 2c). For the $40 \times 40 \times 160 \text{ mm}^3$ specimen, EWs with a size of 40 mm width and 70 mm height were embedded in the specimen (Figure 2d) to evaluate the effect of different embedded electrodes on the FCR response of the SS-HPFRC beam under bending load.

The SS-HPFRC compressive specimens were prepared to deeply understand the FCR response at the compressive part of the SS-HPFRC beam. For compression test specimens, the fresh mixtures were placed into cubic moulds with dimensions of $100 \times 100 \times 100 \text{ mm}^3$. Two EWs with sizes of $100 \times 130 \text{ mm}^2$ were embedded at designated locations within the specimens, with a spacing of 50 mm.

Specimens with sizes of $100 \times 100 \times 100 \text{ mm}^3$ and $40 \times 40 \times 160 \text{ mm}^3$ were utilised to obtain the compressive strength and flexural strength of SS-HPFRCs, respectively.

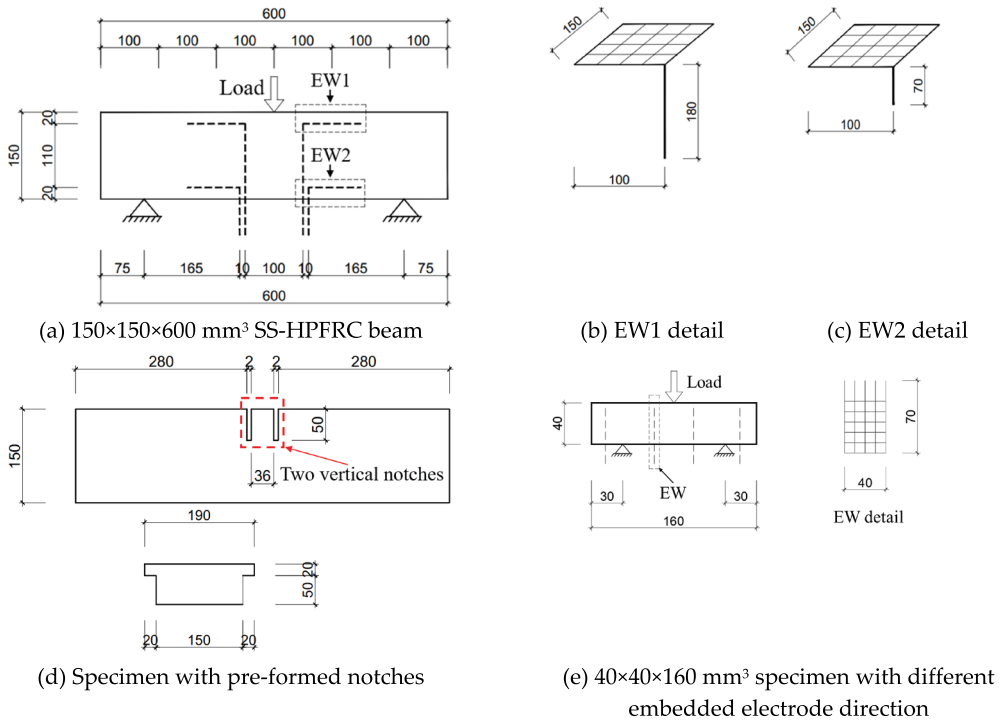


Figure 2. SS-HPFRC specimens.

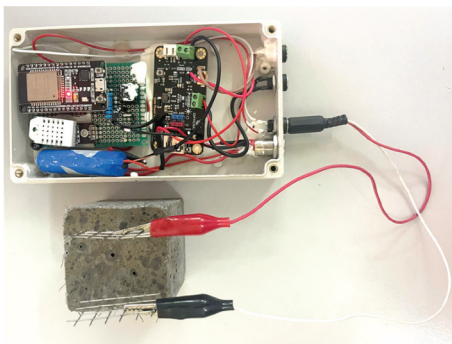
The volume weight was determined based on specimens of $100 \times 100 \times 100 \text{ mm}^3$. At least three specimens of each test were prepared for each matrix composition of SS-HPFRCs.

2.2. Wireless resistance measurement system

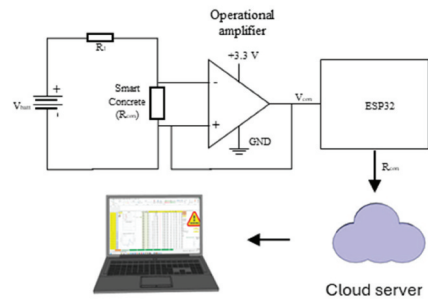
The electrical resistance wireless measurement in this study was called ‘ R_{box} ’ designed based on the wireless measurement system in [31,32]. Le et al. [32] developed a low-cost wireless sensing system to measure the electrical resistance and self-sensing ability of HPFRCs under compression. However, this wireless system is based on Bluetooth technology and is difficult to apply to large-scale structures such as long-span bridges or dams. Figure 3 shows the three main parts of the R_{box} , including (1) a simple circuit of a known supply voltage V_{DC} , a reference resistor ($R_1 = 996 \text{ k}\Omega$), and the SS-HPFRC specimens used to measure the voltage of the HPFRCs (V_{con}); (2) an operational amplifier used in the non-inverting buffer configuration to stabilise the voltage value (V_{con}); and (3) an ESP32 used to connect to a Wi-Fi, and transfer the voltage value V_{con} to the cloud. The reference resistor (R_1) was selected as a suitable value for the electrical resistance of concrete [32]. ESP32 is a series of low-cost, low-power system-on-chip microcontrollers (an Xtensa dual-core (or single-core) 32-bit Lx6microprocessor, operating at 160 or 240 MHz and performing at up to 600 DMIPS) with integrated Wi-Fi connectivity (802.11 b/g/n), dual-mode Bluetooth, a Memory of 520 KiB RAM, 448 KiB ROM, a power amplifier, a low-noise receive amplifier, filters, and power-management modules [33]. In the R_{box} , the ESP32 connected a Wi-Fi and uploaded the data packet including R_{con} and V_{con} to the cloud (Google datasheet). The data transmission rate was one data packet per second. A rechargeable lithium battery was used as a DC power source ($V_{\text{DC}} = 3.3 \text{ V}$) for R_{box} . A solar cell and a solar charger can connect to the lithium battery to charge the battery in case of real-time applications. Figure 3 shows the DC wireless resistance measurement system with a two-probe method.

The electrical resistance of SS-HPFRC (R_{con}) is calculated using Equation (1) [32], based on values of V_{DC} , R_1 , and V_{con} .

$$R_{\text{con}} = V_{\text{con}} \times R_1 / (V_{\text{DC}} - V_{\text{con}}) \quad (1)$$



(a) Wireless measurement system



(b) Wireless resistance measurement detail

Figure 3. Wireless measurement system (R_{box}).

The self-sensing ability of SS-HPFRCs was observed by evaluating the FCR between electrodes under external loads. The FCR of composites is calculated using Equation (2), based on the measured electrical resistance (R) or the electrical resistivity (ρ) between electrodes using two or four-probe measurement methods [19,23,31,32,34–37]. Even though the two-probe measurement method provided a higher electrical resistance value owing to the contact resistance between electrodes and matrices, many studies indicated that the self-sensing abilities of smart concretes would be evaluated by using this method [24,32,34,38–40]. In addition, two probe measurement methods with a simpler test setup and more suitable for application in SHM systems with wireless measurement technology were generally used to evaluate the electrical resistance (R) of SS-HPFRCs under loading.

$$\text{FCR} = [(R - R_o)/R_o] \times 100\% = [(\rho - \rho_o)/\rho_o] \times 100\% \quad (2)$$

$$\rho = R \times (A/L) \quad (3)$$

In Equations (2) and (3) [1], A , L , R_o , and ρ_o denote the cross-sectional area, the distance between the measured two electrodes, the initial electrical resistance, and the initial electrical resistivity, respectively. The electrical resistivity (ρ) is calculated using Equation (3).

2.3. Test set-up

Figure 4a depicts the experimental setup used to measure the electrical resistance of SS-HPFRC specimens under bending loads. Under bending, the SS-HPFRC beam is divided into two main parts: the tensile part and the compressive part. Thus, to deeply understand the FCR response at the compressive part of the SS-HPFRC beam under bending, the self-sensing ability of SS-HPFRCs under compression was investigated (Figure 4b).

A three-point bending test was carried out on ADVANTEST 9 with a 3000 kN capacity. The loading rate for the $150 \times 150 \times 600 \text{ mm}^3$ specimen is 0.05 MPa/s, whereas the loading rate for the $40 \times 40 \times 160 \text{ mm}^3$ specimen is 0.1 MPa/s. Compressive tests were performed using the ADVANTEST 9 testing machine system with a loading rate of 0.5 MPa/s.

A multimeter (INSTEK GDM 9060 multi-purpose resistance metre) and an R_{box} were used to measure the electrical resistance of the tensile and compressive parts in $150 \times 150 \times 600 \text{ mm}^3$ bending specimens, respectively. Besides, the multimeter measured the electrical resistivity responses of $40 \times 40 \times 160 \text{ mm}^3$ bending and $100 \times 100 \times 100 \text{ mm}^3$ compressive specimens. The flexural stress (σ_f) is calculated using Equation (4) [41].

$$\sigma_f = 1.5 \times F_t \times l / (b \times h)^2 \quad (4)$$

where F_t was the external flexural load, l , b , and h are the distance between pillows, width, and height of specimens ($l = 100 \text{ mm}$ and $b = h = 40 \text{ mm}$ for $40 \times 40 \times 160 \text{ mm}^3$ specimens and $l = 450 \text{ mm}$ and $b = h = 150 \text{ mm}$ for $150 \times 150 \times 600 \text{ mm}^3$ specimens). In the

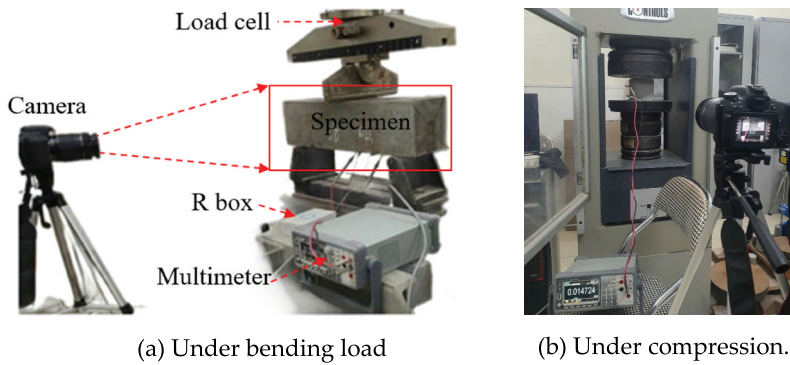


Figure 4. A test setup for measuring the electrical resistance of SS-HPFRCs under external loads.

case of specimens with pre-formed cracks, the h value in Equation (4) is replaced with $(h-h_c)$, where h_c is the height of the pre-formed crack.

The electrical resistance of specimens was measured for approximately 25 minutes to reduce the effects of concrete polarisation due to the influence of using direct current. In general, after 15 minutes, the electrical resistivity of SS-HPFRCs was almost stable. Nguyen et al. [12,13] also observed 15–25 minutes for polarisation effects on the electrical resistivity of HPFRCs with steel fibres. Once the electrical behaviour readings became stable, the electrical resistance measurement and external loading tests were conducted concurrently to capture both stress and electrical resistance variations. The external loads were measured using a load cell embedded in the ADVANTEST 9. Plastic sheets were placed between the specimen surfaces and ADVANTEST 9 to minimise their influence on electrical resistance during testing. Furthermore, a camera was employed concurrently to record the damage propagation images of SS-HPFRCs under external loads.

To further explore the microstructure of SS-HPFRCs, specimens were prepared for scanning electron microscope backscattered electron (SEM – BSE) analysis and tested according to the procedures outlined in [42], using the QUANTA 450 system shown in Figure 5.

3. Results

3.1. The mechanical and microstructure properties of SS-HPFRCs

The addition of short smooth steel fibres notably enhanced the flexural strength of SS-HPFRCs, but had little influence on the compressive strength of SS-HPFRCs. The flexural strength of HPC without fibres was 9.81 MPa. The flexural strength of SS-HPFRCs with 0.5, 1.0, and 2.0 vol% (specimen sizes of 40x40x160 mm³ without embedded electrodes) was 13.5, 15.5, and 17.3 MPa. As the fibre content increased from 0.5 to 2.0 vol%, the flexural strength increased by 28.1%. Kim et al. [43] also reported that the flexural strength of high-strength mortar increased from 5.19 to 11 MPa as the fibre volume content increased from 0.5 to 2 vol%. The bond strength of the fibre bridging the cracked part improved the tensile strength and crack resistance of SS-HPFRCs [44,45]. However, the flexural strength of sensing specimens



Figure 5. SEM-BSE analysis machine.

with sizes of $100 \times 100 \times 400 \text{ mm}^3$ and embedded electrodes was notably lower than that of flexural specimens with sizes of $40 \times 40 \times 160 \text{ mm}^3$ without embedded electrodes. It was 9.16, 10.12, and 11.6 MPa for F0.5C0, F1C0, and F2C0, respectively. A lower flexural strength of sensing specimens would be owing to size and embedded electrode effects. Nguyen et al. [46] also obtained a higher flexural strength of a smaller-sized HPFRCC specimen. It would be explained as follows [46]: according to Weibull's statistical theory, a structural element can be idealised as a chain of numerous sub-elements, where the probability of failure increases with the number of elements, implying that larger specimens are more likely to fail due to the presence of more potential weak points; on the other hand, Bazant's energy-based theory explains the size effect by considering the energy release during fracture; larger specimens store and release more energy into the crack propagation process, thus leading to a greater reduction in strength compared to smaller ones.

The compressive strength of SS-HPFRCs with 0, 0.5, 1.0, and 2.0 vol% steel fibres was 85.21, 89.47, 90.42, and 86.06 MPa, respectively [47]. It was also reported that the addition of steel fibres increased the tensile strength but almost did not improve the compressive strength of high-strength concretes. Besides, as the fibre volume content increased from 0.5 to 2 vol%, the volume weight of SS-HPFRCs increased from 2315 to 2523 kg/m^3 because of increasing fibre weight in the SS-HPFRC matrices. Figure 6 shows the images of fibres at crack paths and the microstructure of the matrix surrounding fibres.

The distribution of fibres in cross-sectional areas of specimens was quite uniform, as shown in Figure 6a. As the fibre content increased, the number of fibres in cross-section and bridging crack parts increased, consequently enhancing the crack resistance and flexural strength of SS-HPFRCs. In general, as can be seen in Figures 6b, c, the microstructure of SS-HPFRCs was quite dense. There were a few pore areas in the matrix surrounding the fibre, which produced a high compressive strength and flexural strength of SS-HPFRCs. The connected pore volume content (CPV) in SS-HPFRCs, determined according to [35], based on measuring the weight of specimens at fully dried and fully saturated stages, as follows:

$$CPV(\%) = (\%) = \frac{W_s - W_{dry}}{\gamma_w \cdot V_c} \cdot 100 \quad (5)$$

where W_s and W_{dry} are the weight (g) of the fully saturated specimen and the fully dried specimen (g), γ_w is the water density ($\gamma_w = 997,000 \text{ g/cm}^3$), and V_C is the volume of the cubic specimens ($V_C = 125 \text{ cm}^3$). The calculated CPV value for F2C0 was 6.2%.

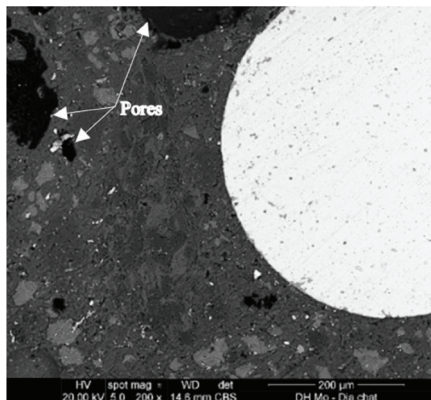
3.2. The initial electrical resistivity of SS-HPFRCs without external loads

Figure 7 shows the polarisation effects on the electrical resistivity of SS-HPFRCs using a single and simultaneous multimeter and R_{box} measurement.

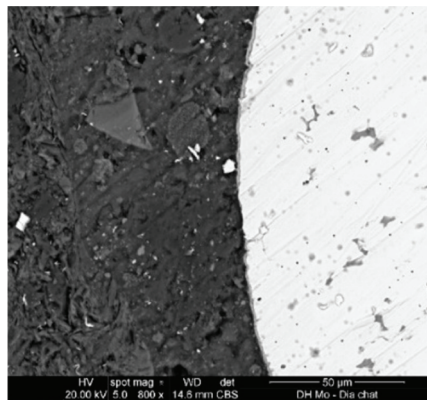
The utilisation of a simultaneous multimeter and R_{box} almost did not influence the polarisation process of SS-HPFRCs but produced a lower electrical resistivity value than one did. Le et al. [40] also reported that two simultaneous multimeters almost did not influence the polarisation process and the electrical resistivity response of smart concretes under external loads. As both the multimeter and the R_{box} were used simultaneously, the higher electrical resistance of SS-HPFRCs would be owing to an increase in the applied voltage to the gauge length measurement. Two probe measurement methods caused the high values of electrical resistivity in Figure 7, which were determined from the measured electrical resistance, including



(a) Cross-section at crack path (F2C0)



(b) Microstructure, Zoom in 200 μm (F2C0)



(c) Microstructure, Zoom in 50 μm (F2C0)

Figure 6. Fiber distribution and microstructure images of matrix surrounding fiber.

both the electrical resistance of composites and the contact resistance between electrodes and composites. However, it indicated the effect of using simultaneous two-measurement machines on the polarisation effects.

3.3. The FCR responses of SS-HPFRCs under bending

Figure 8 shows the FCR response of SS-HPFRCs at the tensile part (Multimeter) and compressive part (R_{box}) in correlation with the flexural stress. Based on the response of FCR, bending stress, and image analyse, the crack generation in stages was observed. Ding Y et al. [48] also used the load and voltage versus time to evaluate the crack sensing ability of a smart concrete beam without the results of deflection. The load-deflection curve of SS-HPFRCs would be analysed experimentally and theoretically in future studies.

Table 2 summarises FCR values at P100 (peak flexural stress point), PA80 and PA50 (points after the peak stress with the flexural stress equal to 80%, and 50% σ_{max} , respectively), and the crack propagation positions.

Figure 9 presents the crack propagation images of SS-HPFRC with 2 vol% steel fibres, and Figure 10 shows the crack images of different SS-HPFRCs at peak stress.

The micro-cracks were observed as the flexural stress reached nearly peak stress. At the peak stress, the crack was opened and propagated (Figure 9). SS-HPFRC without fibres was fractured at peak stress (Figure 10a). In contrast, SS-HPFRCs with steel fibres could continuously resist the load after peak stress with crack opening and propagation. After the peak stress, the main crack propagated from the tensile section to the compressive section. In this study, with a three-point bending test, there was only one main

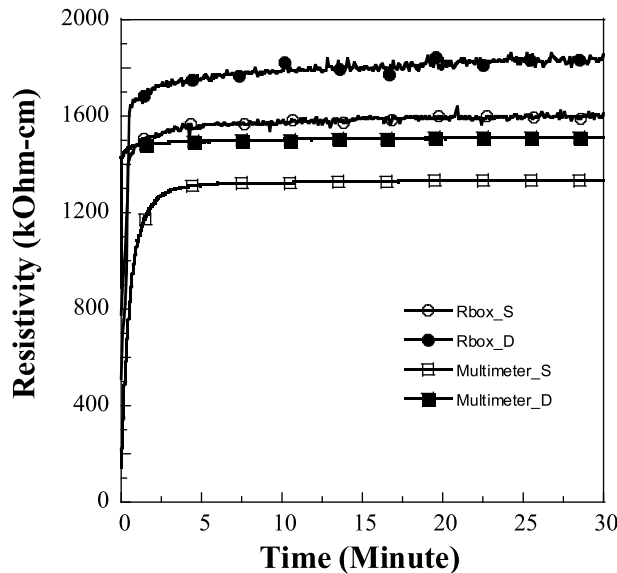
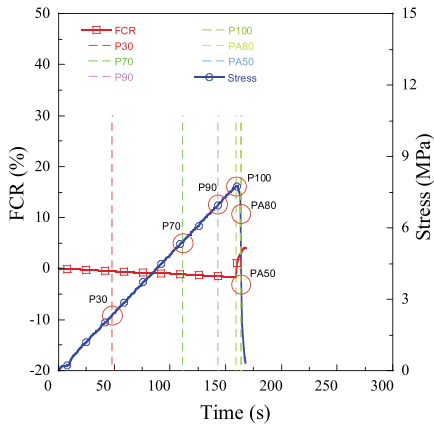
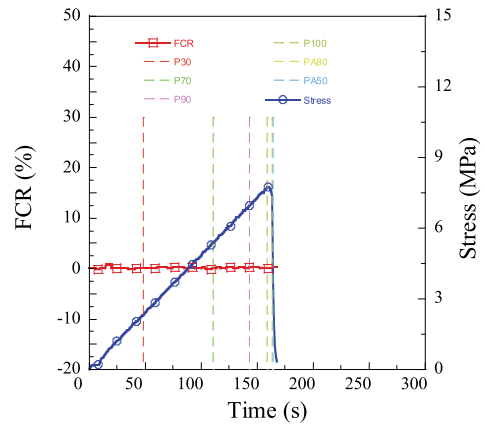
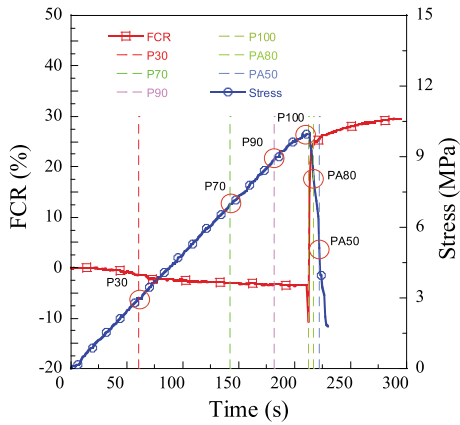


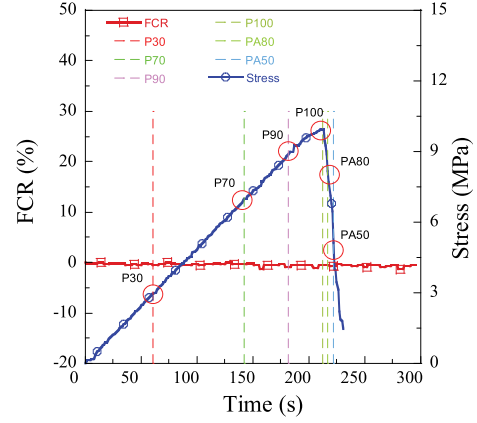
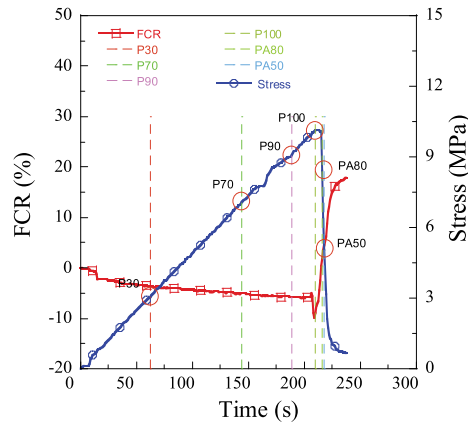
Figure 7. Effects of single or simultaneous multimeter and Rbox measurements on the polarization using two probe measurement methods (S: single measurement; D: simultaneous multimeter and Rbox measurements).



(a) F0C0_Multimeter (Tensile section)

(b) F0C0_R_{box} (Compressive section)

(c) F0.5C0_Multimeter (Tensile section)

(d) F0.5C0_R_{box} (Compressive section)

(e) F1C0_Multimeter (Tensile section)

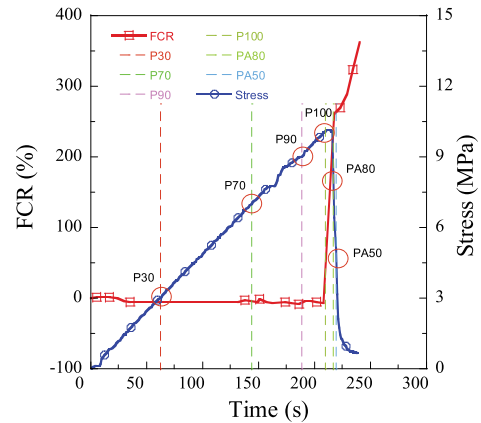
(f) F1C0_R_{box} (Compressive section)

Figure 8. The FCR and flexural stress responses of SS-HPFRCs under bending using simultaneous multimeter and R_{box} .

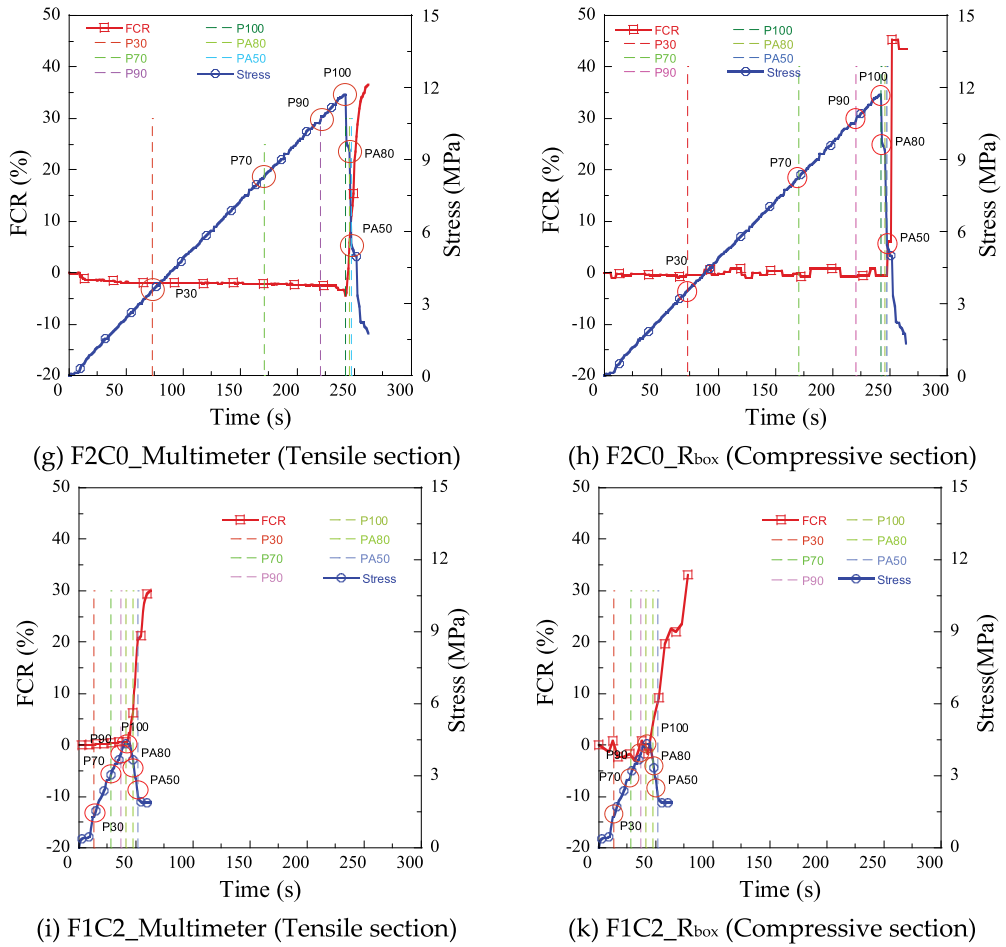


Figure 8. (Continued)

Table 2. FCRs at tensile and compressive sections of SS-HPFRCs under bending.

No	Multimeter (Tensile section)				R _{box} (Compressive section)			
	FCR ₁₀₀ (%)	FCR _{A80} (%)	FCR _{A50} (%)	CP	FCR ₁₀₀ (%)	FCR _{A80} (%)	FCR _{A50} (%)	CP
F0C0	-1.08	0.6	3.0	in	0.21	0.10	0.2	in
F0.5C0	-8.50	25.4	27.0	in	0.10	0.3	0.2	out
F1C0	-9.03	0.2	8.6	in	-3.5	160	260.9	ele
F2C0	-4.8	9.2	19.8	in	0.3	0.50	6.5	in
F1C2	1.1	5.2	21.5	in	0.8	4.2	8.3	in
F1C0_40	0.5	22.6	31.5	in				

CP: crack position compared to the gauge length measurement; ele: crack propagation at the embedded electrode position; in: crack propagation in gauge length measurement; FCR₁₀₀, FCR_{A80}, and FCR_{A50}: FCR at P100, PA80, and PA50, respectively; F1C0_40 means F1C0 specimens with sizes of 40x40x160 mm³.

crack opening and propagating. Besides, in HPFRCs, the crack spacing, crack width, and crack height were theoretically calculated based on the bond strength between steel fibres and matrix, which was obtained through the single pullout test and would not be easily conducted. Thus, the crack width and crack height were observed based on the image

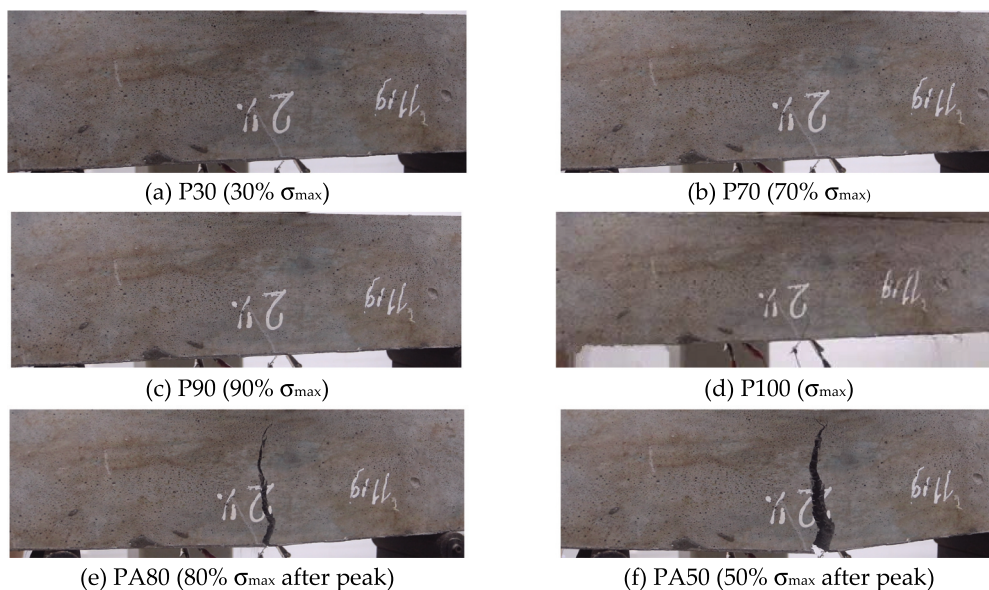


Figure 9. Crack propagation of F2C0 under bending.

analysis. The crack width was calculated based on the ratio between the crack image size at different stages and that at the finalised test stage. Table 3 summarises the crack height and width of SS-HPFRCs, which were determined from the values at the finalised test stage and the ratio between the image crack at the flexural stress stages and the image crack at the finalised test stage. Besides, the SS-HPFRC specimens ($100 \times 100 \times 400 \text{ mm}^3$) produced lower flexural strength values in comparison with the flexural strength of specimens ($40 \times 40 \times 160 \text{ mm}^3$) without embedded electrodes. It would be owing to size effects and embedded electrodes. However, the flexural strength still increased as the fibre content increased.

As can be seen in Figures 9 and 10, the cracks of SS-HPFRCs were first generated in the gauge length measurement at the tensile section but propagated at different positions in the compressive section. The crack was generated in the gauge length measurement at the tensile section for F0C0, F0.5C0, F1C0, F2C0, and F1C2. Then, the crack was propagated in the gauge length measurement of the compressive section for F0C0, F2C0, and F1C2, at the embedded electrode position for F1C0, and out of the gauge length measurement for F0.5C0. The different generation and propagation positions of cracks, which resulted in different FCR responses of SS-HPFRCs under bending, are shown in Figure 8.

3.4. Effect of different directions of embedded electrodes on the FCR response of SS-HPFRCs

Figure 11 shows the FCR response of SS-HPFRC specimens with vertically embedded electrode directions.

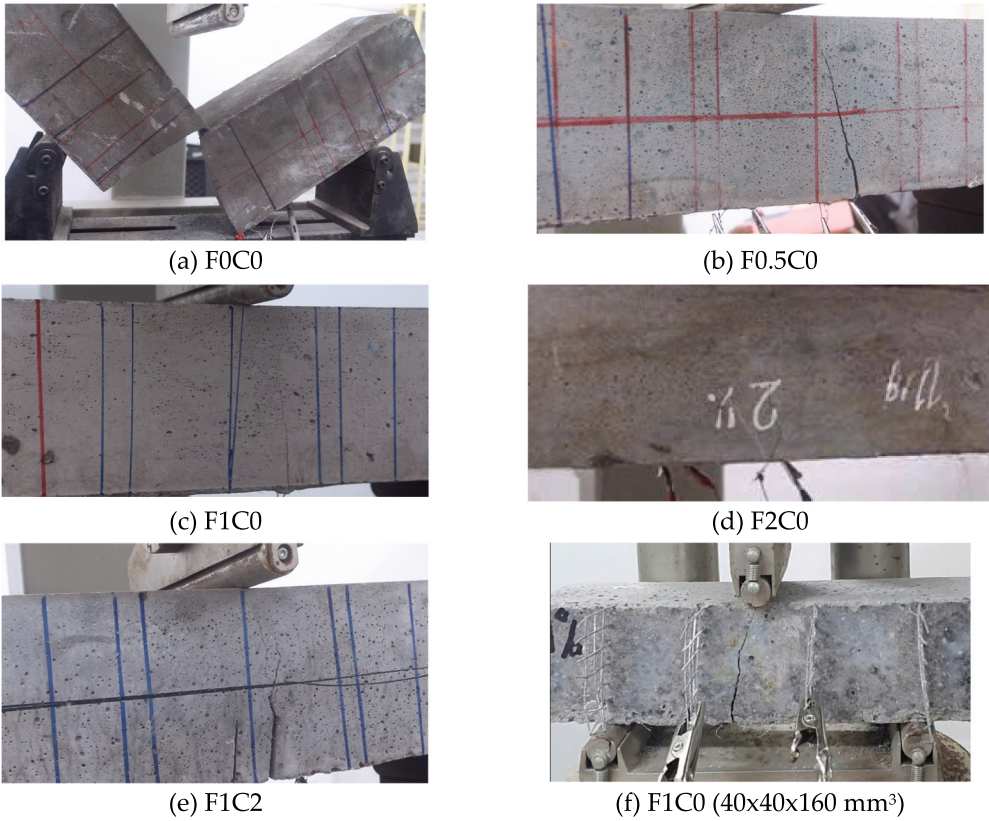


Figure 10. Crack images of SS-HPFRC specimen at the peak flexural stress.

Table 3. Crack width and height of SS-HPFRCs at stress stages under bending.

No	Crack width (mm)			Crack height (mm)		
	P100	PA80	PA50	P100	PA80	PA50
F0C0	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
F0.5C0	2.1	5.4	6.8	86	106	127
F1C0	1.4	8.5	10	54	138	145
F2C0	0.8	11	16.8	72	129	134
F1C2	1.3	8.2	23.7	31	54	58
F1C0_40	1.9	4.3	6.8	30	35	37

In general, the electrical resistivity of SS-HPFRCs was almost unchanged before peak stress or crack generation. After peak stress, the electrical resistivity significantly increased with quickly propagating cracks. As can be seen in Figure 8e, the electrical resistivity decreased with increasing bending load before peak stress. The FCR response of specimens with vertically embedded electrodes was less sensitive than that with horizontally embedded electrodes before peak stress. Under bending, the crack was first generated at the tensile section (bottom of specimens) and propagated to the middle section and then to the compressive section (top of specimens). The generation of microcracks at the tensile section would not influence the conductive network in SS-

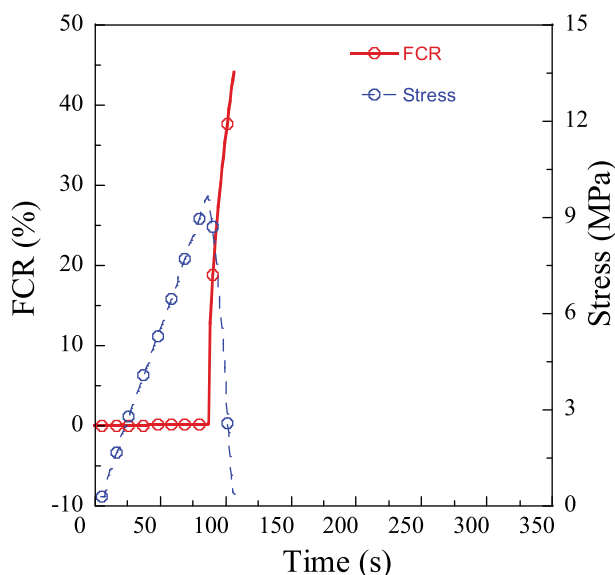


Figure 11. The electromechanical response of F1C0 with a size of $40 \times 40 \times 160 \text{ mm}^3$ under bending load.

HPFRCs with vertically embedded electrodes because the current would transfer through the remained section. Meanwhile, microcracks in the tensile section caused changes in the electrical resistance of SS-HPFRCs with horizontally embedded electrodes, as shown in Figure 8e. Le et al. [23,24,40] indicated that under tension, micro-cracks caused a reduction in the electrical resistivity of smart concretes with short, smooth steel fibres owing to the high electrical conductivity of steel fibres bridging micro-cracks. And then, as the crack opened, the electrical resistivity increased because steel fibres were pulled out from the matrix. Thus, horizontally embedded electrodes produced more sensitivity than vertically embedded electrodes until peak stress.

3.5. The FCR response of SS-HPFRCs under compressive stress

Figure 12 illustrates the FCR response of SS-HPFRCs, while Figure 13 presents the crack propagation images under the compressive stress.

The stress ratio in Figure 12 was the ratio of compressive stress and the maximum compressive stress. The FCR at peak stress was 32.5%, and the maximum FCR was 81.7%. The FCR response would be divided into three stages. The FCR little changed as the compressive stress varied from 0 to 30% peak stress (SS-HPFRCs worked in the elastic stage). Then, the FCR notably decreased even after peak stress until a minimum value during micro-cracks generation and propagation. Finally, the electrical resistivity gradually increased. Le et al. [19,21,37] also obtained a reduction in smart concretes with steel fibres under compression.

As the compressive strain increased, the distance between functional fillers (steel fibres) decreased while the connection between functional fillers increased in the matrix and micro-crack paths. Thus, the electrical resistivity of SS-HPFRCs continuously

decreased after peak stress until a minimum value under compression. Whereas, under bending, at the maximum flexural strength, the tensile part reached the peak stress, and the crack was generated and propagated, whereas the compressive part would be still in the elastic region.

As can be seen in Figure 12, cracks were observed on the surface of the specimens as the compressive stress was around the peak stress ($\sigma_{\max}$). After peak stress, the main crack was continuously opened and propagated. The opened cracks destroyed the conductive network in the SS-HPFRC matrices and consequently caused a slight increase in electrical resistance of the matrices.

4. Discussion

4.1. Detecting damage generation of SS-HPFRCs under bending

The damage generation of SS-HPFRCs under bending can be sensed based on the FCR response at the tensile section. As the crack was generated in the gauge length measurement at the tensile section, the electrical resistivity response of SS-HPFRCs (F0.5C0, F1C0, and F2C0) at the tensile part (Multimeter measurement) would be divided into two main stages corresponding to the crack propagation process. First, the electrical resistivity of SS-HPFRCs gradually decreased as the flexural stress increased from 0 to peak, and then their resistivity significantly increased as the main crack quickly propagated and opened to the compressive section.

Under bending, the cracks generally started at the tensile section owing to the low tensile resistance of concrete as the flexural stress increased to the peak stress. In this

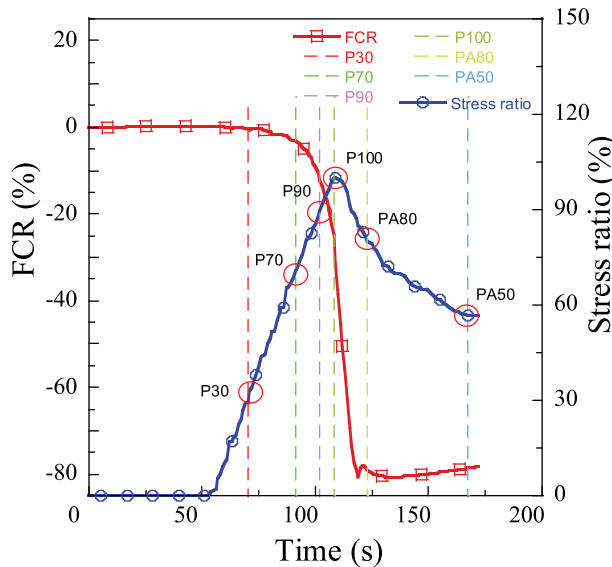


Figure 12. The FCR responses of SS-HPFRCs (F1C0) under compressive stress.

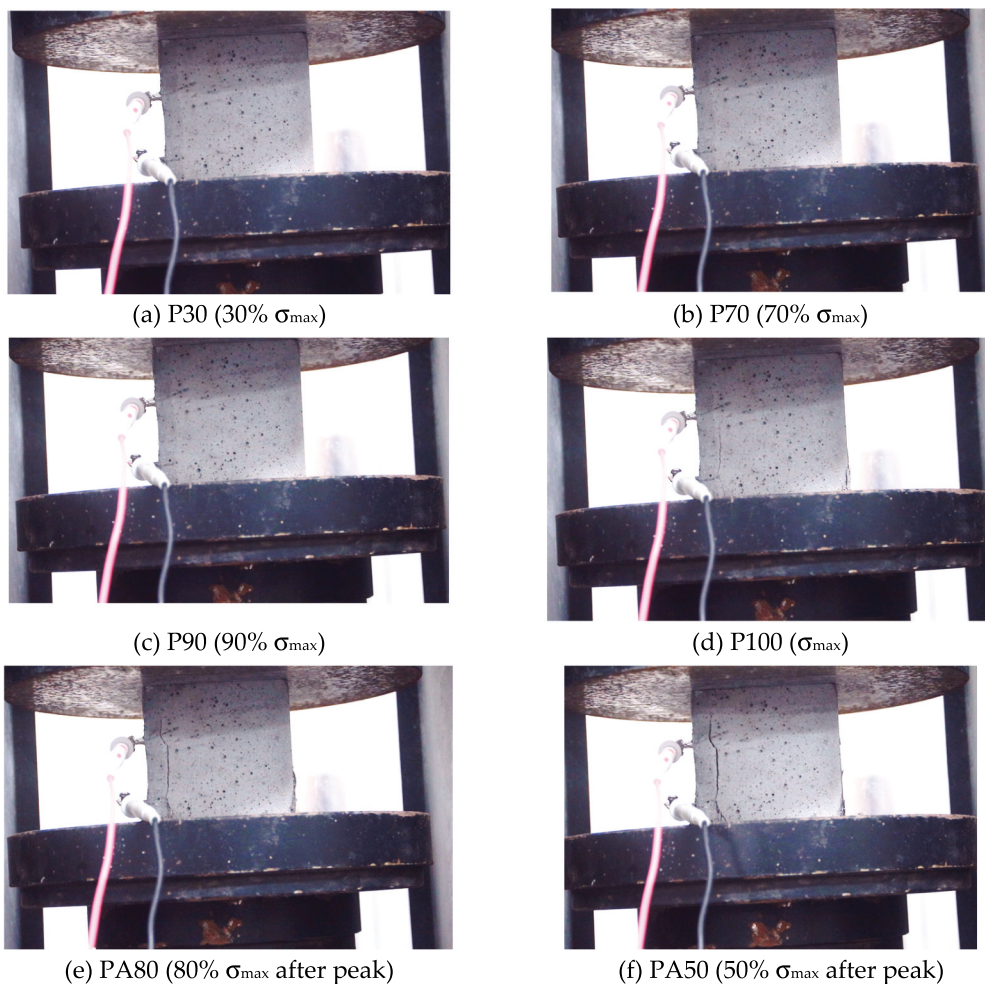


Figure 13. Crack propagation of F1C0 under compression.

stage, fibres still bridge matrices at the crack path. Nguyen et al. [12] and Le et al. [40] indicated that the electrical resistivity of SS-HPFRCs decreased with the generation of micro-cracks under tension. As the fibres and the matrices at the crack path were fully or partially bonded, the significantly lower electrical resistivity of fibres bridging the crack in comparison with that of the composite caused a reduction in total electrical resistivity of SS-HPFRCs between the two electrodes [12,40]. The electrical resistivity of F0C0 without fibres almost levelled off in this stage (Figure 8a).

After peak stress, as the main crack opened and propagated to the compressive section, the flexural stress of SS-HPFRCs with fibres declined, and the electrical resistivity dramatically increased. As can be seen in Figure 5, in this stage, fibres and matrix of SS-HPFRCs would be fully debonded and pulled out at the crack path, which caused an increasing electrical resistivity of SS-HPFRCs [40]. Quickly opened and developed major cracks, resulting in a broken conductive network of composites. Besides, the generation and propagation of major cracks at the embedded electrode position (e.g. Figure 8b for

F0.5C0) caused a significant increase in contact resistance between embedded electrodes and matrices and consequently increased the measured electrical resistance of SS-HPFRCs. The measured electrical resistance between two electrodes included the electrical resistance of the composites and the contacting resistance between the electrode and the composite [1]. Thus, a crack propagation at the embedded electrode broke the electrical conductivity between the electrode and the composite, consequently increasing the measured electrical resistance value.

4.2. Detecting damage propagation of SS-HPFRCs under bending

The damage propagation of SS-HPFRCs under bending can be detected by evaluating the FCR response at the compressive section. A notable increase in the electrical resistivity at the compressive section indicated that the crack had propagated from the tensile section to the compressive section. As can be seen in Figure 8, the FCR of F2C0 and F1C2 clearly increased as the crack opened in the gauge length of the compressive section. Besides, that of F1C0 also significantly increased as the crack propagation at the embedded electrode position.

Under bending, the maximum compressive stress at the compressive section was equal to the maximum tensile stress at the tensile section and equal to the flexural strength of SS-HPFRC beams (varied from 9.16 to 17.3 MPa as the fibre volume content increased from 0.5 to 2 vol%). Thus, under bending, the compressive stress in the compressive section was under 30% of the compressive strength of SS-HPFRCs (varied from 85.2 to 90.4 MPa) and worked in the elastic region.

Based on the electrical resistivity response in Figure 12, the electrical resistivity at the compressive part in the elastic region (before P30) was almost unchanged. Thus, the increase in the electrical resistance of F2C0, F1C0, and F1C2 at the compressive section under bending was owing to crack propagation to the compressive section. The opening of cracks in the gauge length destroyed the conductive network, while the crack propagation at the embedded electrode broke the contact between electrodes and matrices and resulted in an increase in electrical resistivity of SS-HPFRCs. However, the electrical resistivity of F0.5C0 was almost unchanged because the crack propagation was out of the gauge length measurement of R_{box} (Figure 8d). Thus, the electrical resistivity response at the compressive section (R_{box} measurement) of SS-HPFRCs also depended on the position of crack propagation in comparison with the gauge length measurement.

4.3. A conductive network model of SS-HPFRCs under bending

Figure 14 illustrates a conductive network response of SS-HPFRCs under bending to explain the damage-sensing characteristics. The conductive network was built based on images of the microstructure, fibre dispersion at the crack path, and crack propagation images of SS-HPFRCs

Figure 14a presents a simple circuit of the conductive network in SS-HPFRCs. The measured electrical resistance (R_c) included two main parts: the contact resistance between embedded electrodes and matrices (R_{ct}) and the resistance of composites, which involved the electrical resistance of composites at the non-cracked part (R_{co})

and the cracked part (R_{cr}). The R_{ct} depended on the bond of embedded electrodes and SS-HPFRC matrices. R_{co} was mainly influenced by the contact and ionic conductions. The contact conduction between contacted FFs is affected by the content and type of FFs [49]. The ionic conduction is generated in porous solution systems through the movement of ions such as Ca^{2+} , K^+ , OH^- and is significantly influenced by the matrix composition [1]. R_{cr} was significantly dependent on the crack width and fibres bridging the crack (Figure 14b, c). The FCR response of composites can be explained based on the conductive network in composites under external loads.

As micro-cracks were generated inside or on the surface of SS-HPFRCs, fibre-bridging micro-cracks were still fully or partially bonded with matrices under external loads. At the micro-crack path, the ρ_{cr} was equal to the electrical resistivity of steel fibres bridging the crack, which was significantly lower than that of composites, thus, R_{cr} decreased, and consequently, R_c decreased.

As the main crack opened and propagated, the fibre and matrix at the crack paths were pulled out or fully de-bonded, the electrical resistance at the crack path (R_{cr}) was equal to the electrical resistance of the pore path surrounding fibres and significantly higher than that of the composite. Thus, an increasing R_{cr} caused a dramatic increase in R_c . In addition, the crack propagation would break the contacting conduction of embedded wire meshes and matrices, increasing R_{ct} . Thus, in this stage, the increase in electrical resistivity of composites would be owing to increasing R_{cr} or R_{ct} .

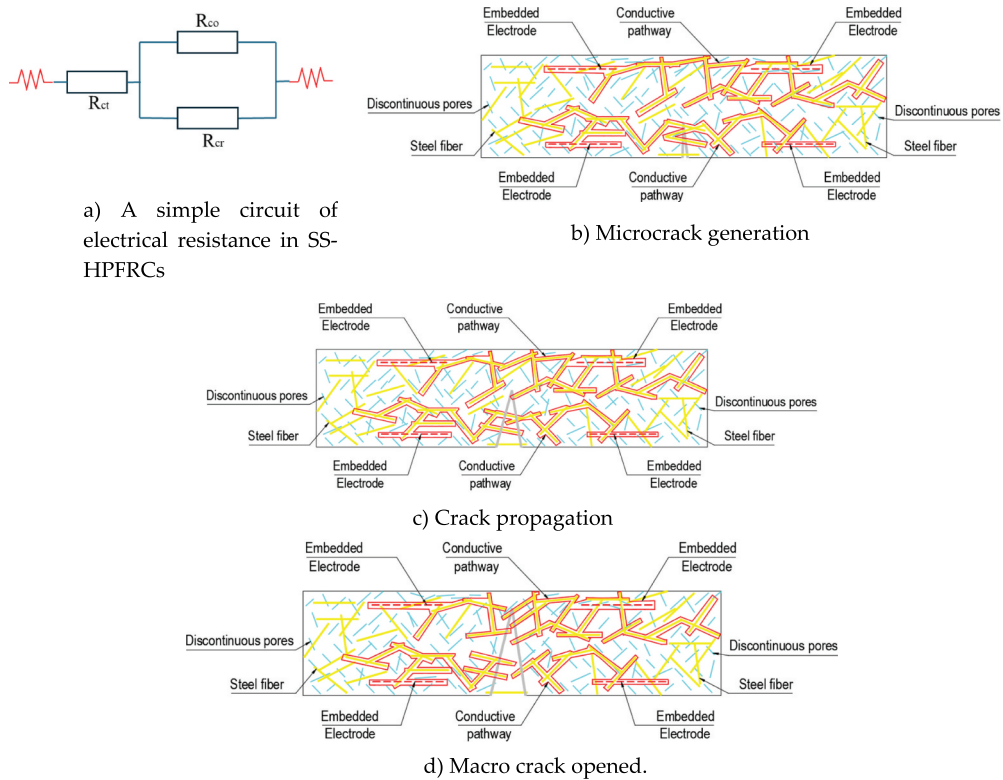


Figure 14. The FCR responses of SS-HPFRCs (F1C0) under compressive stress.

5. Conclusions

This study investigated the damage-sensing characteristics of SS-HPFRCs during crack propagation by measuring the electrical resistance, external load, and capturing video of samples under bending. A simple wireless measurement with two probes was designed to measure the electrical resistivity of smart concretes and transfer the real-time data to a cloud system through an internet connection. The effects of fibre type (steel fibre) functional fillers on the electromechanical response of SS-HPFRCs during crack propagation on the surfaces were analysed. Some conclusions were obtained as follows:

- A main crack was obtained on the surface of the SS-HPFRC beam at nearly peak stress. The flexural strength of sensing specimens ($100 \times 100 \times 400 \text{ mm}^3$) with embedded electrodes was significantly lower than that of specimens ($40 \times 40 \times 160 \text{ mm}^3$) without embedded electrodes, owing to the effects of specimen sizes and embedded electrodes.
- Damages in the SS-HPFRC beam can be sensed based on evaluating the FCR response at the tensile section under bending. The electrical resistivity of SS-HPFRCs with fibres can be divided into two main parts: a gradual decrease with the generation of cracks surrounding peak flexural stress, and a significant increase with the opening of the main crack.
- Damage propagation of SS-HPFRCs can be observed based on the FCR response at the tensile section, incorporating that response at the compressive section. A significantly increasing FCR at both the tensile and compressive sections indicated that the crack had propagated from the tensile section to the compressive section. The propagation of damage at the embedded electrodes produced a significantly higher FCR than that at gauge length measurements.
- The vertically embedded electrodes produced a less sensitive crack propagation of SS-HPFRCs under bending compared to the horizontally embedded electrodes at compressive and tensile sections.
- A conductive network model was developed to explain the FCR response of SS-HPFRCs under bending. The broken conductive network, owing to fibre pullout and the broken connection between electrodes and SS-HPFRC matrices, would be the main reasons for increased electrical resistivity at compressive and tensile sections during the opening of the main crack.

Thus, SS-HPFRCs containing short smooth steel fibres were a potential smart material to apply for high-rise buildings and long-span bridges because of their high-performance properties and self-damage sensing abilities. A combination of SS-HPFRCs with a wireless electrical resistance measurement system would be utilised in the SHM system to detect abnormal phenomena in structures early and provide timely repair and maintenance to prevent catastrophic collapse.

Abbreviations

The following abbreviations are used in this manuscript:

Highlights

- The damage-sensing ability of short smooth steel fibre-reinforced high-performance concrete beams was investigated.
- Damage sensing ability at tensile and compressive parts of the SS-HPFRC beam was evaluated simultaneously.
- A wireless electrical resistance measurement is utilised and presented as suitable for real structure applications.
- The effect of electrode direction on crack detection was evaluated.
- A conductive network of SS-HPFRCs with crack propagation under flexural load was developed.

Author contributions

Thi Nhan Pham, writing – original draft preparation; formal analysis, writing – review and editing; Huy Viet Le, writing – original draft preparation; formal analysis, writing – review and editing; Sy Duc Nguyen, Van Kien Dang, Viet Nghia Nguyen, Anh Tu Do, and Duy Liem Nguyen, writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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