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Scientific paper

Kinematics on Split-Tensile Test of Fiber-Reinforced Concrete by AE

Mielke R. I. A. J. Mondringin¹ and Masayasu Ohtsu²

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Abstract

In order to study tensile failure in fiber-reinforced concrete, split-tensile tests were conducted. Disc-shaped samples of mortar, plain concrete, steel-fiber reinforced concrete (SFRC) and polyvinyl-alcohol-fiber reinforced concrete (PVAFRC) were tested. Fracture mechanisms at the meso-scale are identified by applying SiGMA (Simplified Green's functions for Moment tensor Analysis) procedure of acoustic emission (AE). In fiber-reinforced concrete, a self-healing draws an attention in concrete engineering. The effect could bridge opened (tensile) cracks due to hydration of unreacted cement. Since the crack width of the tensile crack is a key issue, kinematical information of the crack formation process is investigated in the split-tensile test prior to experimental confirmation on the self-healing effect. It is found that sliding motions on the crack surface are more dominantly observed in PVAFRC than those in mortar, plain concrete and SFRC, prior to reaching the final stage, i. e. possibly under the service load. This suggests that self-healing products, which could be generated at the cracked surface, could play the more effective role in PVAFRC for bridging meso-scale cracks due to tight spaces (gaps) across fibers.

1. Introduction

Due to loading, aging and environmental effects, a variety of cracks are generated in concrete. In particular, quasi-brittle failure under tensile load has been a long-engaging subject in concrete, which could present a serious threat to the performance of concrete structures. Concrete is a multi-scale material at the levels of observation, and the current research of concrete material focuses on three distinct levels of the micro-, meso- and macro-levels (van Mier 1997). Since plain concrete mostly fails due to propagation of tensile cracks, the reinforcement is applied to concrete structures. In the case of fiber-reinforced concrete (FRC), cracking is readily protected at the meso-scale, which results in the fact that the resistance against impending failure at the macro-scale could be improved.

Crack nucleation at the meso-scale inside concrete produces transient elastic waves as acoustic emission (AE). It is known that AE techniques can play a significant role for monitoring, predicting and clarifying the failure processes in concrete (Grosse and Ohtsu 2008). Since the tensile strength of concrete is normally evaluated by the split-tensile (Brazilian) test, the moment tensor analysis of AE was applied to clarify the tensile failure process at the meso-scale in concrete (Reinhardt *et al.* 2007; Mondringin *et al.* 2011). Concerning the

tensile strength of concrete, a variety of findings have been attained and recently the nucleation of the fracture process zone is highlighted in fracture mechanics (Bazant 1993; Bazant *et al.* 1994). From AE research, it is clarified that similar nucleation processes of the fracture process zone could reasonably lead to comparable tensile strengths by the split-tensile test and by the direct tensile test (Ohtsu *et al.* 2011).

In addition to the resistance to nucleation of tensile cracks, the effect of self-healing FRC draws an attention in concrete engineering (Homma *et al.* 2009). It is reported that with the aid of fibers, the formation of self-healing products (calcium carbonate crystal) becomes easy to bridge the crack surfaces due to tight spaces across the fibers. In addition, the recovery rate of the strength is superior in polyethylene fiber to that of steel fiber.

With respect to the self-healing effect, mechanisms of tensile failure in fiber-reinforced concrete were studied in the split-tensile tests (Ozbay *et al.* 2013). According to our recent research (Mondringin and Ohtsu 2012), failure process of FRC in the split-tensile test is known to be similar to those of mortar and plain concrete. In all the cases, AE sources are observed only near the loading plates in the beginning stage. Then, the sources (cracks at the meso-scale) propagate to the center of the specimen where the maximum tensile stress is reached. Finally, macro-scale cracks are abruptly formed as the specimen is split apart, creating AE cluster along the final failure planes.

These results show that failure processes in cementitious materials without fibers are similar to those of materials reinforced with fibers. But, the contribution to the self-healing effect is preferably observed in fiber-reinforced materials. Further, the effects of fibers are different between a stiff fiber (steel) and a flexible fiber

¹Ph. D. Student at Graduate School of Science & Technology, Kumamoto University, absent from the Faculty of Engineering, Sam Ratulangi University, Indonesia.

²Professor, Graduate School of Science and Technology, Kumamoto University.

E-mail: ohtsu@gpo.kumamoto-u.ac.jp

(polyethylene). Consequently, kinematics of mortar, plain concrete, steel-fiber reinforced concrete (SFRC) and polyvinyl-alcohol-fiber reinforced concrete (PVAFRC) in the split-tensile tests are studied prior to experimental confirmation of the self-healing effect. In the present paper, by applying SiGMA-AE analysis to the split-tensile tests, kinematics of these materials are clarified and the kinematical contribution of fiber reinforcement to the self-healing effect is discussed.

2. Experiments

2.1 Materials

Mixture proportions of mortar, plain concrete, SFRC and PVAFRC tested consisted of the same water-to-cement (W/C) ratios and the volume ratios of fine aggregate (s/a) of 0.45 and 0.44, respectively. In plain concrete, SFRC and PVAFRC, the ratio of cement to fine aggregate by weight was 1: 2.4. For these mixtures, the maximum coarse aggregate size was 20 mm. By employing the ordinary Portland cement, the cut-fiber of 30 mm length and approximately 0.4 mm diameter for SFRC and polyvinyl-alcohol-fiber of 30 mm length and approximately 0.012 mm diameter for PVAFRC were added by 0.3 % of concrete volume.

A slump and air content were controlled as 8 cm and 6 %, respectively, by using air-entrained admixture. For each mixture, 6 cylindrical specimens of 100 mm diameter and 200 mm length were made for a compression test and a split-tensile test. For AE observation in the split-tensile test, one specimen of 150 mm diameter and 300 mm length was made for each mixture. All specimens were removed from molds after 24 hours and moisture-cured in the standards room at 20° Celsius. After 28-day moisture-curing, compressive strengths by the compression tests and tensile strengths by the split-tensile tests were obtained, as well as P wave velocities. Results are summarized in **Table 1**. Because the volume ratio of fibers are 0.3 %, the compressive strengths are comparable in all concrete and the increase in the tensile strength of SFRC and PVAFRC are a little compared to that of plain concrete.

Following 28-day moisture curing, the cylindrical

Table 1 Strengths of concrete.

Concrete	Compressive strength (MPa)	Tensile strength (MPa)	P wave velocity (km/s)
Mortar	29.1	2.19	3.57
Concrete	23.9	2.30	3.87
SFRC	25.2	2.49	3.15
PVAFRC	23.8	2.64	3.88

Table 2 Optimal AE sensor array estimated for location analysis.

Coordinates	X (cm)	Y (cm)	Z (cm)
Channel 1	6.5	2.5	11.3
Channel 2	6.5	7.5	3.8
Channel 3	6.5	7.5	11.3
Channel 4	6.5	2.5	3.8
Channel 5	4.0	0.0	1.2
Channel 6	4.0	0.0	3.0
Channel 7	4.0	10.0	12.0
Channel 8	4.0	10.0	3.0

specimens for AE tests was cut into two disc-shaped specimens of 150 mm diameter and 100 mm thickness.

2.2 Test procedure

During the split-tensile tests of disc-shaped specimens, AE signals were detected by employing AE Win SAMOS (PAC). Eight sensors of 150 kHz resonance (R151-AST) were attached to the specimen. The frequency range was 10 kHz to 2 MHz and total amplification was 60 dB gain (40 dB gain in a pre-amplifier and 20 dB in a main amplifier).

In order to determine sensor locations, a simulation analysis was performed beforehand. The velocity of P waves was set to be 4000 m/s and arrival time were estimated with 1 μ sec. sampling. It was found that computational errors of source locations were the minimum within 1.6 mm in the case of the sensor array shown in **Fig. 1**, of which coordinates are given in **Table 2**.

In order to keep a room for sensor attachment, steel blocks of dimensions 10 cm x 5 cm x 2 cm were inserted between the specimen and the loading plates as shown in **Fig. 2**. At the upper loading plate, a loading-cell was set

Fig. 1 Disc specimen and AE sensor array (mm).

Fig. 2 Set-up for the split-tensile test.

between the loading plate and the steel block to measure the loads.

3. Analyses

3.1 Theory of elasto-statics

Stress distribution in a disc subjected to two concentrated diametrical forces is postulated in elastostatics (Timoshenko and Goodier 1970) as shown in **Fig. 3**, and formulated,

$$\sigma_{xx}(x, y) = \frac{2P}{\pi DL} - \frac{2P}{\pi L} \left[\frac{x^2(R-y)}{(x^2 + (R-y)^2)^2} - \frac{x^2(R+y)}{(x^2 + (R+y)^2)^2} \right] \quad (1)$$

$$\sigma_{yy}(x, y) = \frac{2P}{\pi DL} - \frac{2P}{\pi L} \left[\frac{(R-y)^3}{(x^2 + (R-y)^2)^2} - \frac{(R+y)^3}{(x^2 + (R+y)^2)^2} \right] \quad (2)$$

Where P is the applied load, L is the thickness of the

Fig. 3 Configuration of the split-tensile test.

disc, D is the diameter. σ_{xx} and σ_{yy} are normal stresses in the directions perpendicular and parallel to the load, respectively. As well known, in the case $x = 0$, Eqs. 1 and 2 become,

$$\sigma_{xx}(0, y) = \frac{2P}{\pi DL}, \text{ and } \sigma_{yy}(0, y) = \frac{2P}{\pi DL} - \frac{2P}{\pi L} \left[\frac{1}{R-y} + \frac{1}{R+y} \right] \quad (3)$$

The equations above assume a point load on the disc. According to the experimental set-up in **Fig. 2**, the load was actually considered to be distributed over a finite area. This is because a steel block is inserted between the loading plate and the specimen. For the case that pressure P is applied over two diametrically opposite arcs of angular width 2α , as given in **Fig. 4** (Procopio *et al.* 2003). Stresses along the principal diameters in a circular disc with radius R are given by the following relations.

$$\sigma_{xx}(0, y) = \frac{2P}{\pi} \left[\frac{(1 - y^2/R^2) \sin \alpha}{1 - 2y^2/R^2 \cos \alpha + y^4/R^4} - \left(\frac{1 + y^2/R^2}{1 - y^2/R^2} \tan \alpha/2 \right) \right] \quad (4)$$

$$\sigma_{yy}(0, y) = \frac{2P}{\pi} \left[\frac{(1 - y^2/R^2) \sin \alpha}{1 - 2y^2/R^2 \cos \alpha + y^4/R^4} + \left(\frac{1 + y^2/R^2}{1 - y^2/R^2} \tan \alpha/2 \right) \right] \quad (5)$$

The effect of the width of loading area was intensively researched (Rocco *et al.* 1999), and it was reported that the variations in the tensile strengths could result in up to 25 %. Because the strength is not a main target of the research, the formulae above are taken into account.

3.2 AE-SiGMA procedure

The moment tensor, M_{pq} , is defined (Grosse and Ohtsu 2008),

Fig. 4 The case of distributed load in the split-tensile test.

Fig. 5 Crack models for AE sources.

$$M_{pq} = C_{pqjk} n_k l_j \Delta V, \quad (6)$$

Where $\mathbf{n}$ is the unit normal vector to the crack surface and $\mathbf{l}$ is the unit vector of crack motion. ΔV is the crack volume, corresponding to the integration of crack motion over the crack surface. The physical unit of the moment tensor [Nm] is derived from the elastic constants C_{pqjk} [N/m²] times the crack volume ΔV [m³].

In order to determine components M_{pq} of the moment tensor, SiGMA (Simplified Green's functions for Moment tensor Analysis) procedure has been developed (Ohtsu *et al.* 1998). The amplitude of the first motion $A(\mathbf{x})$ in AE waveform is derived as a simplified formula,

$$A(\mathbf{x}) = \frac{C_s \text{Ref}(\mathbf{t}, \mathbf{r})}{R} R r_p r_q M_{pq}. \quad (7)$$

Here C_s is the calibration constant, Ref is the reflection coefficient between the direction vector $\mathbf{r}$ of the distance R from AE source to the observation point $\mathbf{x}$ and the direction vector $\mathbf{t}$ of sensor sensitivity. After the location analysis by a multi-channel system, all variables in Eq. 7 are known except the moment tensor M_{pq} . Thus, the components of the moment tensor can be determined by applying more than 6-channel recording system. To perform the location analysis, arrival times of AE waves should be determined, and then the amplitudes of the first motions are to be estimated. To this end, a software for automated detection of the arrival time and the amplitude is developed (Ohno *et al.* 2008).

The eigen-values of the moment tensor are to be composed of the combination of the shear crack and the tensile crack. The decomposition leads to the shear component (X), the deviatoric tensile component (Y), and the hydrostatic component (Z) of the tensile crack.

In the present SiGMA code, AE source with the shear ratio $X > 60\%$ is classified as the shear cracks, one with $X < 40\%$ as a tensile crack and one with $40\% < X < 60\%$ is classified as a mixed-mode crack. The crack-motion vector $\mathbf{l}$ and the normal vector $\mathbf{n}$ in Eq. 6 are also determined from three eigen-vectors.

Results are visually displayed, by using a graphic software (Light Wave 3D, New Tek). Three models of these cracks are illustrated in Fig. 5. Cracks are classified into three types of shear, mixed-mode, and tensile, and their crack planes normal to vectors $\mathbf{n}$ are illustrated by circles and directions of cracks motions $\mathbf{l}$ shown by arrows.

4. Results and discussion

4.1 Results of AE analyses

AE observations in the split-tensile tests were conducted for two specimens of all mixtures. Results of the same mixture were so similar that results of only one specimen are presented and discussed below.

a) Mortar specimen

A relation between loads and AE hits in mortar is illustrated in Fig. 6(a). Here, AE hits imply the number of AE counts detected at all 8 sensors for 10 seconds. Before the load reaches to 22 kN, a few AE hits are detected. This period is marked as Stage 1 in the graph. In between 22 kN to 43 kN, AE hits are gradually observed and the number of them increase. The period is marked as Stage 2. Afterwards, the applied load reaches its peaks, and significantly large amounts of AE hits are observed within approximately 20 seconds. This is marked as Stage 3. In Fig. 6(b), a relation between accumulated AE hits and AE events at three stages is given. The number of AE events implies that the number of AE sources analyzed by SiGMA. So, kinematics of AE events of locations, crack types and crack orientations are determined. It is seen that 164 AE events are analyzed in the mortar specimen, although more than 1500 hits (12000 in total /8 channels) are detected. Still, the trends of generation of meso-scale cracks are similar.

Based on the previous research (Mondringin and Ohtsu 2012), it is regarded as the failure process up to

Fig. 6 AE activities in mortar specimen.

Fig. 7 Results of SiGMA in mortar specimen.

Stage 2 correspond to those under the service load. At Stage 1, a few cracks at the meso-scale are generated as mostly hidden cracks. Then, at Stage 2, some surface cracks are eventually observed prior to impending failure at Stage 3. Because we are interested in the self-

healing effect under the service load, crack kinematics up to Stage 2 are discussed, later, in detail.

Crack locations, crack types and their orientations of AE events are shown in **Fig. 7**. At Stage 1, AE sources are observed only near the loading plates in the diametrical section. 15 AE events of total 164 AE events are identified, where the dominant cracking modes are 4 tensile-cracks and 9 mixed-mode-cracks. At Stage 2, cracks propagate into the center of the specimen. Toward the final at Stage 3, cracks coalesce and propagate into the whole cross-section and the specimen is split apart which is marked by the solid line. The fact actually suggests that the fracture process zone is created around the final crack surface. Here, the shear-mode cracks are dominantly observed.

b) Concrete specimen

A relation between loads and AE hits are shown in **Fig. 8(a)**. A few AE hits are detected until 25 kN of the applied load at Stage 1. Then, in between 25 kN to 48 kN at Stage 2, the number of AE hits increases gradually. Eventually, at Stage 3, they are acceleratedly generated. A relation between accumulated AE hits and AE events are plotted in **Fig. 8(b)**. AE generation behavior in the concrete specimen is similar to that of the mortar specimen.

AE events analyzed by SiGMA are plotted in **Fig. 9**. At Stage 1, only 6 events are plotted. They are located around the top and the bottom zones of the specimen, suggesting crack nucleation at the meso-scale near the loading plates. AE activity near the loading plates is further accelerated at Stage 2. It is noted that all the types of cracks at the meso-scale are mixed up at the stage. Toward the final at Stage 3, cracks coalesce and propagate onto the whole cross-section. AE cluster at the elevation view is again in remarkable agreement with the final tensile crack at the macro-scale, which is marked by the solid line.

c) SFRC specimen

The relation between loads and AE hits is illustrated in **Fig. 10(a)**. AE activity under loading is also classified into three stages. It is clearly observed that AE activity at Stage 3 is even higher than that of plain concrete

Fig. 8 AE activities in concrete specimen.

Fig. 9 Results of SiGMA in concrete specimen.

in Fig. 8. This suggests that more cracks are generated at the final stage. Before reaching around 42 kN at Stage 1, few AE hits are observed. It may suggest that cracks at the meso-scale are prevented by the reinforcing effect of fibers.

(a) Load vs. AE hits

(b) Accumulated AE hits vs. AE events

Fig. 10 AE activities in SFRC specimen.

In between 42 kN to 56 kN at Stage 2, AE hits are steadily observed. At Stage 3, AE hits are acceleratedly generated. The relation between accumulated number of AE hits and AE events is shown in Fig. 10(b). A generating trend of AE events is similar to that of AE hits. So, it is understood that quite actively AE sources are observed at only Stage 3.

Results of SiGMA are illustrated in Fig. 11. In total, 100 AE events are detected and analyzed. At Stage 1, tensile-mode and mixed-mode cracks are dominant with 14 AE events in total, while 8 AE events of shear cracks are detected. At Stage 2, the number of shear cracks increase gradually. At both Stage 1 and Stage 2, AE sources are only observed around loading plates at the top and the bottom of the specimen. At Stage 3, AE sources are intensely observed at the left side of the specimen as shown in Fig. 11(c), as crack distribution is biased at the left side in the side view. As a matter of course, the location of the main crack in the elevation view is in remarkable agreement with AE cluster.

d) PVAFRC specimen

In Fig. 12, the relation between Loads, AE hits and AE events are shown. It is observed that until 28 kN at Stage 1, there is no significant AE events detected. In between 28 kN to 42 kN at Stage 2, the number of AE hits gradually increases. At Stage 3, there is very significant increase of AE hits.

Results of SiGMA are shown in Fig. 13. 159 AE events in total are analyzed in this specimen. At Stage 1, only 1 tensile cracks and 2 mixed-mode cracks are observed. At Stage 2, the number of shear cracks increases up to 70 AE events in total, while tensile cracks only increase moderately with 5 AE events and mixed-mode with 4 AE events. In a similar manner to the steel fiber reinforced concrete, crack nucleation starts at Stage 2. When the strength of specimen material is reached, a macro-cracks is formed, and the dramatic increase in AE events is observed.

4.2 Discussion

a) Effect of loading

In Fig. 14, tensile stresses σ_{xx} distributed along Y-axis are shown. Based on the test results, the load P is as-

Fig. 11 Results of SiGMA in SFRC specimen

sumed as 50 kN. It is demonstrated that the tensile stress is constant according to Eq. 3 as 2.12 MPa, which are equivalent to the tensile strengths of all mixtures in **Table 1**. In the case of distributed force with 5° angle in Eq. 4, the tensile stress further increases toward the loading

Table 3 Loading stages classified in 4 kinds of specimens.

Concrete	Upper-bound of Stage 1 (%)	Upper-bound of Stage 2 (%)
M	42.3	82.7
C	48.0	92.3
SFRC	70.0	93.3
PVAFRC	58.2	87.5

plate (at the top in the graph). In contrast, the compressive stresses along Y-axis are calculated from Eqs. 3 and 5 and shown in **Fig. 15**. They increase similarly toward the loading plate, and almost reach 50 MPa, which corresponds to the compressive strengths of all the mixtures as listed in **Table 1**. These results imply that cracks at the meso-scale could be generated as both tensile and compressive cracks near the loading plate. As demonstrated in **Figs. 7, 9, 11, and 13**, all the kinds of crack types are observed at Stage 1 near the loading plates.

b) Loading stages

Although classification of loading stages is quite empirical, classified results of AE events are summarized in **Table 3**. Here, the upper-bounds of the loading stages are denoted as the percentage to the final load. Concerning the upper-bounds of Stage 2, they are quite similar as almost 90 %. In contrast, the upper-bounds of Stage 1 in mortar and concrete are low, compared with those of fiber-reinforced concrete. Thus, the effect of the reinforcement to protect crack nucleation at Stage 1 is demonstrated. It is well known that the fiber could resist for cracking in concrete. Results suggest that the resistance are to be effective until the upper-bound of Stage 1.

According to the previous study (Denneman *et al.* 2011), two peaks of the loading curve are stated, and they conclude that the first peak load should be applied to Eq. 3 to estimate the tensile strength of fiber-reinforced concrete. Because the first peak load might be observed following Stage 2, this strength could correspond to the strength of concrete constrained by fibers. Without fiber-reinforcement, after reached the peak loading, the specimen is split apart, while the specimen

Fig. 12 AE activities in PVAFRC specimen.

Fig. 13 Results of SiGMA in PVAFRC specimen.

being bridging by fiber-reinforcement could restrain the tensile stress. Consequently, it is considered that the effect of fibers is to be physically observed up to Stage 2.

c) Crack evolution

Regarding the failure mechanisms, results of SiGMA are considered as similar, as that start at the contact between the specimen and loading plate, and in the diametrical section they propagate to the center of the specimen. After the maximum tensile stress being reached at Stage 3, the specimen is split apart. A criterion for classifying AE sources is based on the shear ratio X . This is because it is assumed that a crack motion on the crack surface consists of both an opening motion and a lateral motion. Since two vectors $\mathbf{l}$ and $\mathbf{n}$ are neither parallel nor perpendicular, both opening and sliding vectors are considered to simultaneously exist on the crack surface. Virtually, crack (dislocation) motion occurs as separating into internal surfaces F^+ and F^- as illustrated in Fig.

Fig. 14 Distributions of tensile stresses along the Y-axis. in Eqs. 3 and 4

Fig. 15 Distributions of compressive stresses along Y-axis in Eqs. 3 and 5.

Fig. 16 Motion of crack surface as AE source.

16, where the motion vector consists of not only an opening vector but also a sliding (lateral) vector. As a result, classification of AE source as a tensile crack or a shear crack suggests neither a pure tensile crack (mode I) nor a pure shear crack (mode II and mode III). It is also noted that AE waves (elastic waves) are modeled as to be nucleated by the displacement discontinuity (dislocation) on the crack surface, where the effect of a crack-tip is kinematically neglected. Thus, cracking modes in fracture mechanics are not directly associated with the classification of cracks by SiGMA. Based on the shear ratio, the source is actually classified into just a dominant type of crack motion at the meso-scale.

Concerning the effect of crack evolution process on the self-healing, a key parameter is the crack width (opening vector in Fig. 16). This is because tight crack widths are likely to promote the healing (Ozbay *et al.* 2013). With this respect, classified AE events up to Stage 2 are summarized in Fig. 17. It is noted that these

Fig. 17 AE events classified up to Stage 2.

are classified by the motions at the crack surface shown in Fig. 16. Consequently, shear-type cracks imply that the sliding motion is more dominant than the opening motion. In the mortar specimen, a few shear-type cracks are observed. This implies that the opening motions, including the mixed-mode are dominant because of no inclusion of coarse aggregate. The number of shear-type cracks increases in plain concrete, compared to mortar. It could be associated with the presence of coarse aggregate.

Although the number of events increases in SFRC, the ratios of shear, mixed-mode and tensile are similar to those of concrete. In contrast, the number of AE events analyzed are equivalent to SFRC in PVAFRC. However, the increase of shear-type cracks is remarkable. This results from the fact that the sliding motions at the crack surface are emphasized because the stiffness to the shear stress of PVA fiber is lower than that of steel fiber.

In relation to the self-healing effect, these results suggest that under the service load up to Stage 2, meso-scale cracks are generated. Due to the resistance to the tensile stress in FRC, more AE events are observed than those in mortar and concrete. Due to the high stiffness of steel fiber, not only shear-type cracks but also the tensile- and mixed-mode type cracks are observed at the meso-scale. The opening vectors in SFRC might result in the difficulty to be healed, because of fairly large gaps at the cracking surface. In contrast, the sliding vectors are dominant in PVAFRC. Thus, the self-healing effect could contribute to good bridging between the cracking gaps at the meso-scale.

5. Conclusions

Kinematics of tensile failure in concrete are clarified by SiGMA, as the crack accumulation process at the meso-scale. Following conclusions can be drawn:

1. Due to the resistance to the tensile stress in fiber-reinforced concrete, more AE events are observed than those in mortar and concrete. Although the number of AE events increases in SFRC specimen, the ratios of shear, mixed-mode and tensile are similar to those of plain concrete.
2. Because of the high stiffness of steel-fiber, not only shear-type cracks but also the tensile- and mixed-mode type cracks are observed at the meso-scale. The opening motions at the crack surface in SFRC might

result in the difficulty to be healed under the service load, due to fairly large gaps at the cracking surface.

3. The number of AE events analyzed are equivalent to SFRC in PVAFRC, while the increase in shear-type cracks is remarkable. Thus, the sliding motions at the crack surface are dominant because the stiffness to the shear stress of PVA fiber is lower than that of steel fiber.
4. In PVAFRC, the self-healing effect could contribute to good bridging between the cracking gaps at the meso-scale. This suggests that the formation of self-healing products plays an effective role due to tight spaces across fibers.

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