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Shear cracking behavior of pre-damaged PVA-aggregate mixed ECC beams: direct observation using DIC

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Abstract

Normal polyvinyl alcohol-engineered cementitious composites (PVA-ECC) have high mechanical performance but are susceptible to shear cracking. It has been found recently that the shear resistance can be largely improved by including coarse aggregates. However, under complex stress conditions, the mechanism of shear movement and the contribution from coarse aggregate remains unclear. This paper presents an experimental investigation of the shear cracking behavior of pre-damaged PVA-ECC beams with a mixture including coarse aggregate. Symmetric and antisymmetric loading tests were carried out to examine the effect of coarse aggregate under different stress rotation fields. To clarify the shear cracking mechanism, digital image correlation (DIC) was applied to observe the development of cracks and strain localization in the shear span of the PVA-ECC beams. The results obtained from the DIC and conventional measurements reached a good agreement, which confirmed that it is reliable to monitor complicated fracture processes using the DIC technique. The shear cracking mechanism of the PVA-ECC beam under complex stress conditions is analyzed. The collaboration of coarse aggregate was observed from the orientation of the secondary cracks, which is less dependent on the precracks. The crack opening and sliding are largely limited due to the reduced anisotropic effect of the predamage. Therefore, using the DIC technique, the positive effect of coarse aggregate is verified, and the shear cracking mechanism of pre-damaged PVA-ECC beams is revealed from direct observations.

Keywords: PVA-ECC, DIC, coarse aggregate, shear performance, complex stress

1. Introduction

Since it is a durable construction material, concrete has been widely used in many infrastructures. However, conventional concrete has low tensile/shear resistance, and the flexural/shear failure in reinforced concrete structures is often brittle [1-2]. To improve the ductility of concrete materials, fiber reinforcement is considered an excellent option to enhance their post-peak tension-softening behavior under tensile load. In the past decades, significant progress has been achieved in developing high-performance fiber-reinforced cementitious composites (HPFRCCs). After first cracking, these materials can develop various degrees of tensile ductility, frequently followed by a macroscopic pseudo-strain-hardening response [2]. According to this definition, HPFRCC is differentiated from normal fiber-reinforced concrete (FRC), as illustrated in **Fig. 1**. HPFRCC has a strain hardening branch after the first cracking because of the occurrence of multiple cracks, while conventional FRC does not experience this phenomenon.

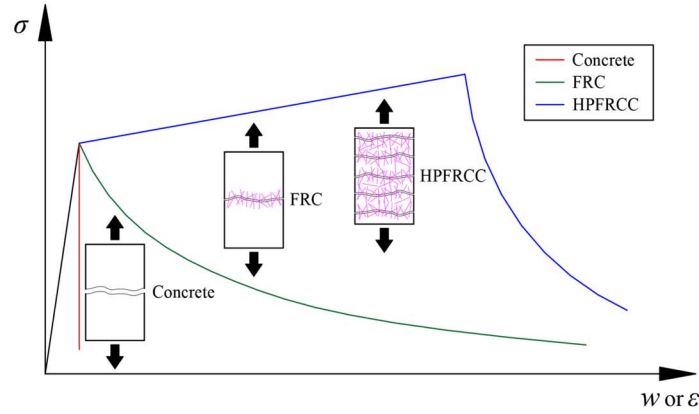


Fig. 1 Stress-strain (or crack opening) relationship of concrete, FRC, and HPFRCC under uniaxial tension [3]

One type of HPFRCC, engineered cementitious composites (ECC), was proposed by Li and Leung three decades ago [4]. In contrast to conventional cement-based materials, ECC has a moderate amount (about 2% by volume) of short discontinuous fibers. Owing to the fiber-bridging effect, ECC shows superior tensile-strain-hardening behavior, multiple microcracking characteristics, excellent damage tolerance, and self-healing performance [5–10] [9,11,12]. For the reinforcing fibers, one typical one is polyvinyl alcohol (PVA) fibers. It has attracted extensive attention due to its ultrahigh toughness, high tensile strength, high cracking resistance, durability, and great crack width control [13,14]. Since the micromechanical characteristics of the fiber/matrix interface are intentionally adjusted, the PVA-ECC can release energy through multiple microcracking with fracture widths of less than 100 μm [13]. The PVA-ECC could have a tensile strain capacity of more than 4% and durability levels approximately 200-600 times compared to conventional concrete [14,15].

Owing to the abovementioned advantages, PVA-ECC is applied as a strengthening material or structural elements such as beams, pavements, tunnels, and slabs [16–19]. Several studies have investigated the performance of steel-reinforced PVA-ECC beams under static loading [20–22]. The flexural behavior and ductility of PVA-ECC beams improve significantly compared to plain RC beams, with a 14.8% higher load-carrying capacity and an improvement of 2.4 times in the ultimate mid-span deflection [20,23]. In addition to increasing flexural performance, applying PVA-ECC has also been found to enhance the shear resistance. This provides a high potential to reduce the need for shear reinforcement bars in structural elements [24]. Shimizu et al. [21] and Zhao et al. [22] found that the shear behavior of PVA-ECC beams is much superior to that of plain RC beams. The shear strength of the PVA-ECC beam was approximately 1.91 times that of the RC control beam. Owing to the diagonal multiple cracking patterns and the stable crack development, shear bearing capacity can be primarily reversed even after shear cracking [25]. Suryanto et al. [26–28] studied the shear capacity and failure mechanism of PVA-ECC and correlated them with experimental data by utilizing an explicit shear transfer model and anisotropic stress-strain fields. This study found that the failure mechanism of ECC beams was affected not only by the breakdown of tensile stress transfer at cracks but also by shear transfer mechanisms. Although the shear resistance of ECC beams is better than that of normal concrete, it has recently been found that cracks in ECC are still susceptible to shear due to the absence of coarse aggregates. A significantly deficient shear resistance can develop across the cracks, eventually generating tangible crack slip [29]. On the other hand, when coarse aggregate is added to the ECC, the tortuosity of the fracture path tends to increase. This leads to a tough matrix that can delay crack initiation and prevent steady-state flat crack propagation [30], increasing the shear crack resistance [28]. Also, the flexural performance of ECC is decreased due to the reduced number of fibers in the crack section where the coarse aggregate has occupied, as well as the crack bridging stress [28]. It is the reason why coarse aggregates generally are eliminated from ECC mixtures. Therefore, it remains unclear

for the shear performance of PVA-ECC with coarse aggregates under a stress rotation field.

When the PVA-ECC is used as a structural element, it is essential to understand both the wide ranges of strain distributions and local-scale crack behavior. However, conventional measurement methods of strain in concrete are not capable of accurately obtaining these two features at the same time. To solve this problem several techniques have been proposed to solve this problem, such as digital image correlation (DIC), which can provide high accuracy to full-field surface displacement/strain fields [31]. By using the DIC technique, not only the crack propagations of FRC and the crack width development of PVA-ECC beams have been successfully analyzed, but also the monitoring of the shear crack-opening and crack-slip behavior of prestressed concrete beams [20,32–34]. Thus, the DIC technique has great potential to be applied to observe the wide ranges of strain distribution and reveal the crack sliding mechanism of PVA-ECC beams.

This paper presents an experimental study on the shear cracking behavior of PVA-ECC beams with and without coarse aggregate. Symmetric and antisymmetric loading tests are carried out under a complex stress rotation field. The DIC technique was adopted to monitor the full-field displacement and strain in the shear span of the PVA-ECC beams. The local shear crack opening and sliding mechanism of PVA-aggregate mixed ECC beams was revealed cautiously. The results of this study are significant to understanding the shear cracking mechanism of pre-damaged PVA-ECC with coarse aggregates.

2. Test programs

2.1 Specimens and loading method

This study prepared two types of PVA-ECC beams, with and without including coarse aggregate, for the tests. The coarse aggregate was mixed at a ratio of 15% by volume, and the maximum size of the aggregate was 9.5 mm, concerning the previous study [28]. The diameter and the length of the PVA fiber was 0.04 mm and 12 mm, respectively, with a tensile strength of 1,600 MPa. The composition of the materials is the same for all experimental series, as shown in **Table 1**. Bending and compression tests were carried out to obtain the material properties of PVA-ECC with and without coarse aggregates. The specimens for the bending tests were prismatic and had a dimension of 100 x 100 x 400 mm³, while those for the compression tests were cylindrical with a diameter of 100 mm and a length of 200 mm, as shown in **Fig. 2**. The test was conducted under displacement-controlled loading at a rate of 0.8 mm/min. In the case of the bending tests, the load-deflection curve was continuously monitored throughout the entire test until the specimens reached failure.

Table 1 Mix proportion of PVA-ECC

W/(C+FA) (%)	Water (kg/m ³)	S/(C+FA) (%)	PVA fibers (%), in vol.
42.2	350	70	2.0

Note: W = water, C = cement, FA = fly ash, S = sand.

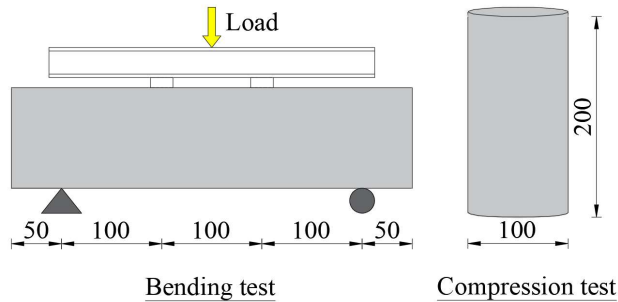


Fig. 2 Specimens for bending and compression tests (Units: mm)

The results of the bending tests are presented in **Fig. 3**, and the results of the compression tests are given in **Table 2**. In the context of the materials codes, NE is normal ECC, EC is ECC with the inclusion of the coarse aggregate, while S and A indicate the materials that are used in the symmetric and antisymmetric loading tests, respectively. For example, NE-S is the normal ECC material that is used in the symmetric loading test. The results show that the flexural strength of PVA-ECC material was reduced due to the incorporation of the coarse aggregate, as explained in the previous section. However, the coarse aggregates have an insignificant effect on the compressive strength of PVA-ECC materials.

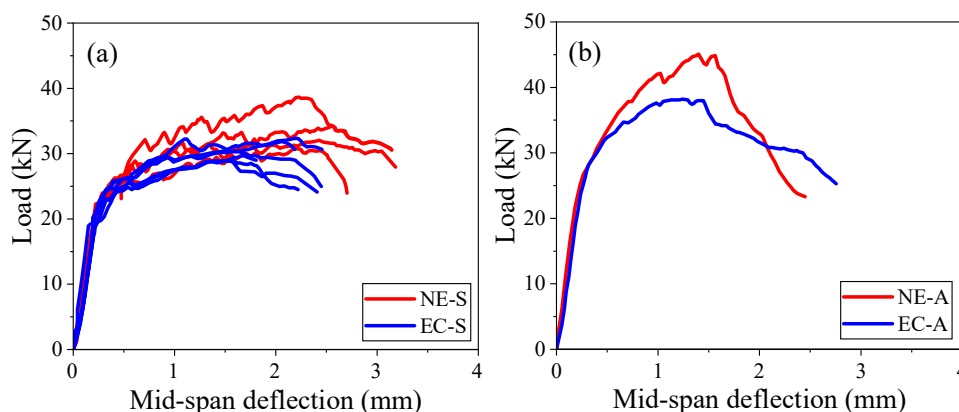
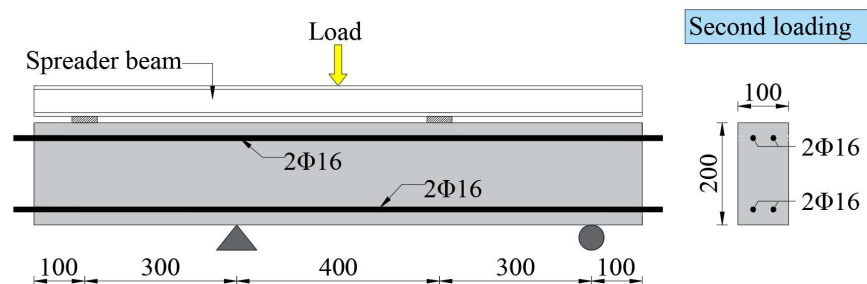
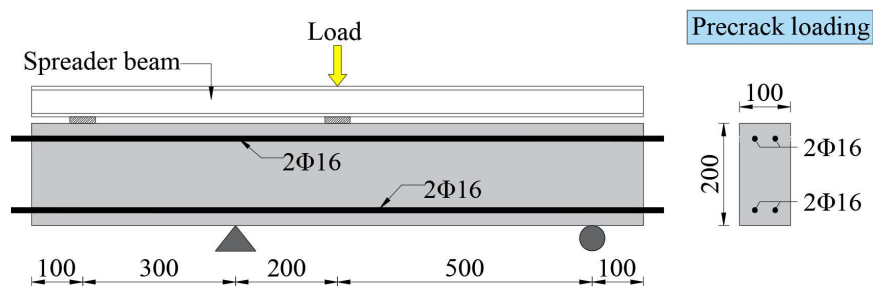
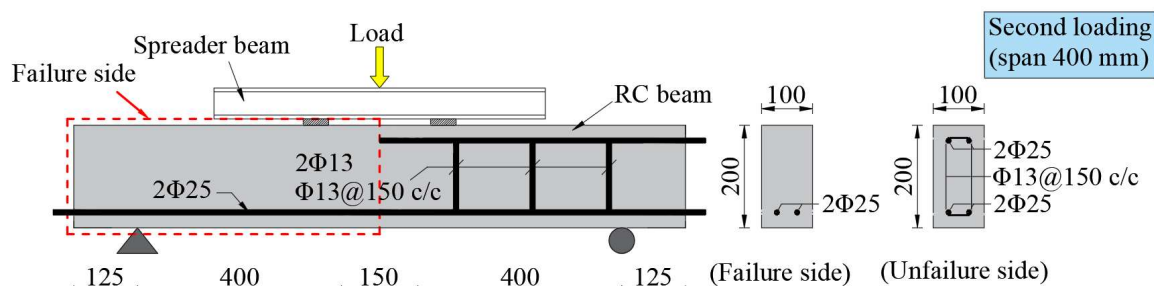
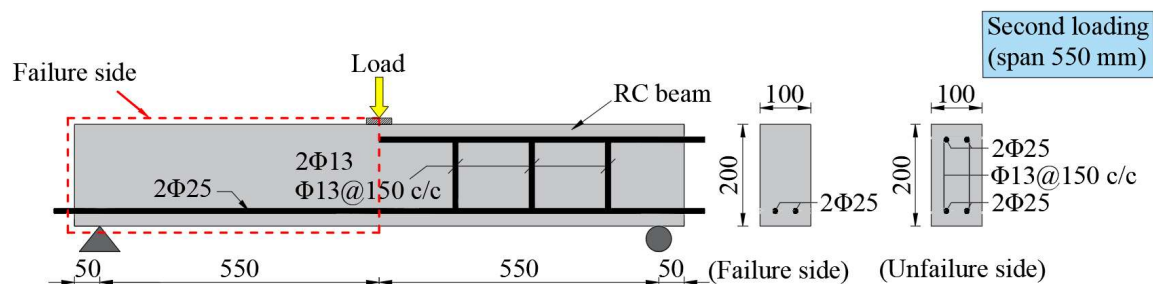
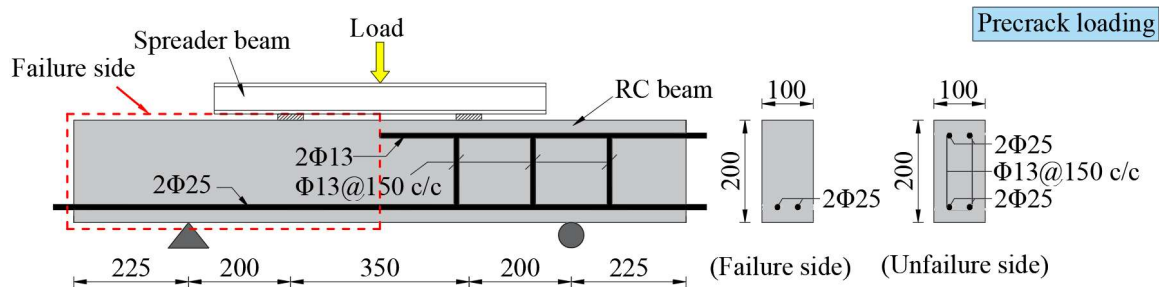


Fig. 3 Bending test results of PVA-ECC materials

Table 2 Mechanical properties of materials

Materials	Diameter (mm)	Compressive strength (MPa)	Elastic modulus (GPa)	Yield strength (MPa)
PVA-fiber	0.04	-	-	-
NE-S	-	35.6	-	-
NE-A	-	37.8	-	-
EC-S	-	37.8	-	-
EC-A	-	34.5	-	-
SD390	13	-	190	390
USD685	16	-	190	685
USD685	25	-	190	685

To consider the complex stress conditions that may occur in real structures, symmetric loading tests were performed to introduce the precracks. Due to the existence of the precracks, simultaneous cracks opening and sliding can occur and their effect on the shear behavior of PVA-ECC beams can be examined. Also, these precracks were intended to analyze the contribution of the coarse aggregates to the improvement of shear resistance on the crack surface in PVA-ECC beams. The precracks were first introduced in a short span set to 200 mm, as illustrated in **Fig. 4(a)**. Subsequently, in the second loading, the shear span was expanded to 550 mm or 400 mm (see **Fig. 4(b-c)**), followed by reloading until failure. The shear span was changed to affect the direction of the precracks, as well as the localized stress conditions. On this basis, the crack resistance mechanism of coarse aggregates could be further clarified.



(e) Second loading with a span of 400 mm

Fig. 4 Specimen details and loading conditions of beam tests in: (a-c) symmetric and (d-e) antisymmetric loading tests: (all units in mm)

To determine the load levels of the precracks, a preliminary experiment on the same specimen was performed. From the results, the load level was set to 350 kN. For the other conditions, precracks were set almost to fail, where the increase in load during the test became nearly flat in the load–deflection curve. Meanwhile, in the “non-precracked” case, the span was kept through the whole loading process under the condition of a second loading. The load levels of precracks for all test series are provided in **Table 3**. The labeling scheme of the tested beams was arranged in the format T-P-L-C with T = type of the test, P = with or without precrack (in the case with precrack, the number indicated the shear span at the second loading), L = load level of precrack, and C = with or without coarse aggregate. For example, S-P550-350-C refers to a PVA-aggregate mixed ECC beam with a load level of precrack of 350 kN and shear span of the second loading of 550 mm, tested by symmetric loading tests.

Table 3 Detail of specimens

Type of test	Test series	Span at failure (mm)	Load level of precrack (kN)	Material	a/d	
					Primary loading	Secondary loading
Symmetric	S-NP-550-E	550	-	Normal ECC	3.14	-
	S-NP-550-C	550	-	ECC + Aggregate	3.14	-
	S-P550-350-E	550	350	Normal ECC	1.14	3.14
	S-P550-350-C	550	350	ECC + Aggregate	1.14	3.14
	S-P550-F-E	550	458	Normal ECC	1.14	3.14
	S-P550-F-C	550	479	ECC + Aggregate	1.14	3.14
	S-P400-F-E	400	469	Normal ECC	1.14	2.29
	S-P400-F-C	400	489	ECC + Aggregate	1.14	2.29
Antisymmetric	A-NP-400-E-A	400	-	Normal ECC	2.29	-
	A-NP-400-C-A	400	-	ECC + Aggregate	2.29	-
	A-P400-F-E-A	400	?	Normal ECC	1.14	2.29
	A-P400-F-C-A	400	?	ECC + Aggregate	1.14	2.29

Note: S = symmetric loading test; A = antisymmetric loading test; NP = non-precracked; P = precracked (the number after P indicates the shear span at the second loading); E = normal ECC; C = ECC + coarse aggregate; F = load level of the precrack is close to bearing capacity of the beam.

The beam has a total length of 1200 mm with a cross-section of 100 x 200 mm². The tension, compression, and shear reinforcements have diameters of 25 mm, 13 mm, and 13 mm, respectively, as shown in **Fig. 4**. The large tension reinforcement was selected for the beams to ensure that the primary failure mode was shear rather than flexural failure. This will allow a more accurate analysis of the shear strength of the beam. Furthermore, the shear and compression reinforcements were set on only one side of the specimen so that the failure would occur on the other side. In this case, shear failure could be observed more effectively.

Moreover, two series of antisymmetric loading tests were also performed, including non-precracked and precracked conditions. The precracks were introduced almost to fail, where the load increase was nearly flat. However, the load level of precrack in the anti-symmetric loading test was not recorded. The beam has the same dimension as that of symmetric loading tests. However, to observe only the shear resistance of the PVA-ECC beams, the diameter

of the tension and compression reinforcement of the specimens was 16 mm, whereas the shear reinforcements were not used, as shown in **Fig. 4(d-e)**. In the first loading, the shear span of the beam was set to be 200 mm. Then, it was enlarged to 400 mm and continued with the second loading until failure.

2.2 Digital Image Correlation (DIC) technique

Conventional deformation measurements, such as strain gauges and linear vertical displacement transducer (LVDT), can only provide limited data that depend on the location of the instruments, while the DIC technique can measure the strain in a wide region with high accuracy. Moreover, the DIC technique could obtain the local displacement of cracks, such as crack opening and crack sliding. Therefore, this study adopted this method to measure the deformation in the fracture zone and reveal the shear cracking mechanism of PVA-ECC beams.

The procedure of the image analysis method developed at the Futaba Laboratory of the Tokyo Institute of Technology by Watanabe et al. [35] was used in this study. This method can directly observe the real-time strain development on the surface of RC beams during the loading test. The visualized strain distribution can evaluate the strain concentration area and predict the failure mode of RC beams before the load reaches the maximum level. **Fig. 5** shows the procedures of the image analysis system. First, seals with a diameter of 5 mm were placed on the surface of the specimen at a spacing of 20 mm. When the specimen was installed at the loading position, the camera was calibrated to correct the distortion of the lens of the camera. Then, the location of all the seals was captured in pictures during the loading process (every 10 kN), and the center coordinates of all seals were extracted using HALCON software. Finally, using the obtained reference point coordinates, the strain was calculated using a finite element method named the nine-point isoparametric method, and the surface strain distribution was extracted as a contour diagram.

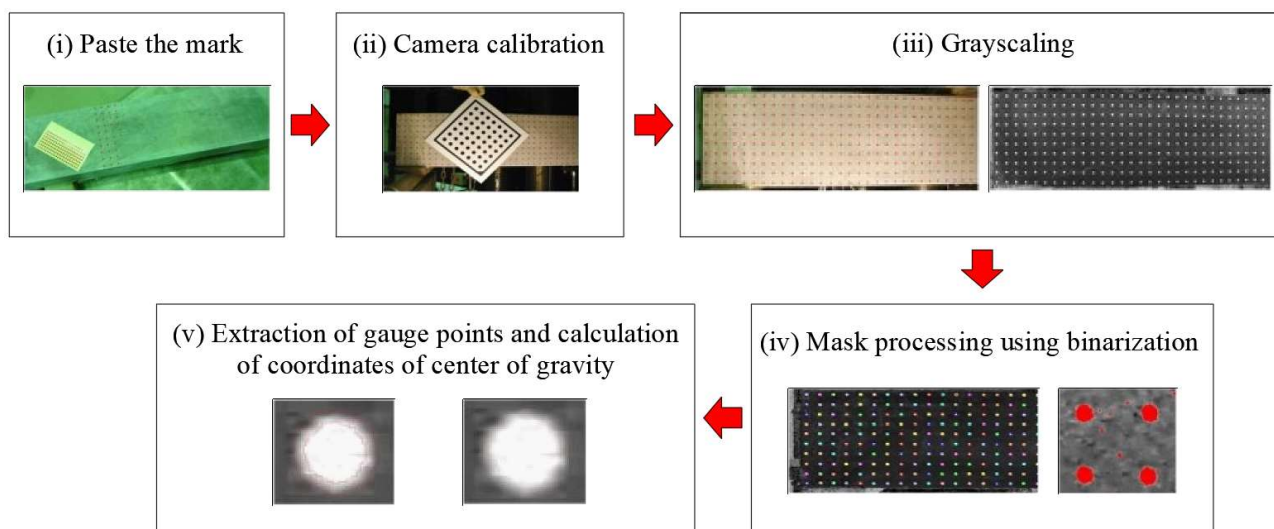


Fig. 5 Flow of image analysis method

The scheme of the DIC system arrangement is shown in **Fig. 6**. Some light-emitting diode (LED) lights were used for lighting, and they were set at a distance of approximately 40 cm under the specimen so that all the reference points could be extracted by image processing. The conventional measurements, LVDT, and strain gauges were also installed to compare and validate the accuracy of the DIC technique. The strain gauges were set on the backside surface of the specimens to avoid interference from the DIC detection.

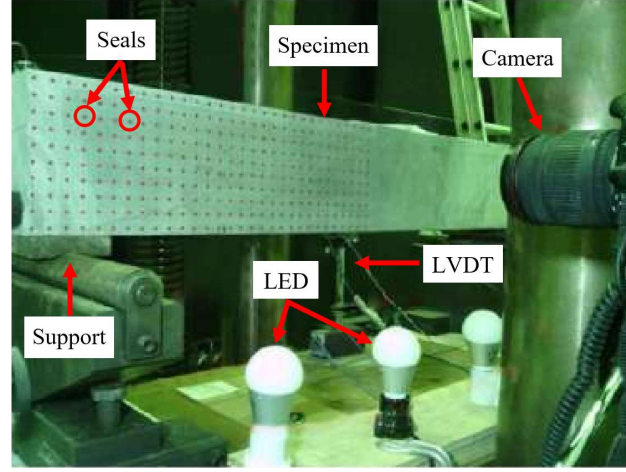


Fig. 6 Scheme of DIC measurement

In this study, the evaluation method is provided in two ways. The contour figure was generated to evaluate the shear distribution over a wide range. On the other hand, a certain range of points was selected on the shear failure crack to evaluate the local cracking behavior, and the strains against the crack opening direction were calculated. To understand the localized behavior of the PVA-ECC beam under complex stress condition, converting strain data to local crack displacement is essential, ensuring precise and sensitive detection of subtle changes. Since the primary concern in this study is to understand the initial crack formation mechanism, possible measurement noise is tolerable at this moment but it should be avoided in the future for better accuracy.

A finite element method was utilized, employing nine-node isoparametric elements to discretize the test specimen. The positioning of these elements was determined based on the centroid coordinates of the gauge. The center of gravity coordinates of the gauge was determined through the analysis of images captured before and after the loading commenced. Subsequently, the displacement values (u, v) were calculated. The computation of displacement (u, v) for an arbitrary point within the nine-point isoparametric element, as shown in **Fig. 7**, relied on the nodal displacements (u_i, v_i) and the shape function $N_i(\xi, \eta)$. These relationships were expressed in Eqs. (1) and (2).

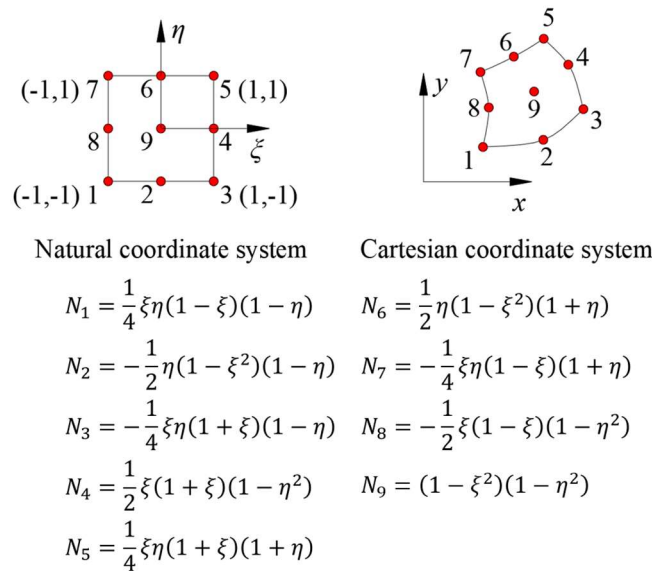


Fig. 7 Investigation of local crack behavior [36]

$$u = \sum_i N_i(\xi, \eta) u_i \quad (1)$$

$$v = \sum_i N_i(\xi, \eta) v_i \quad (2)$$

where $N_i(\xi, \eta)$ represents the shape function of node i within the 9-node isoparametric element, (ξ, η) are the natural coordinates, and (x, y) stand for the Cartesian coordinates of the element. The displacements u_i and v_i describes the displacement of the node in the x and y directions, respectively. Additionally, within the element, three critical strain components are computed: general strain (ε), maximum principal strain (ε_1) and minimum principal strain (ε_2). These strain components can be calculated using the following equations:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \partial u / \partial x \\ \partial v / \partial x \\ \partial u / \partial x + \partial v / \partial y \end{Bmatrix} \quad (3)$$

$$\varepsilon_1 = \frac{1}{2}(\varepsilon_x + \varepsilon_y) + \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad (4)$$

$$\varepsilon_2 = \frac{1}{2}(\varepsilon_x + \varepsilon_y) - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad (5)$$

where ε_x and ε_y are the strain in the x and y directions, respectively, while γ_{xy} is the shear strain.

The PVA-ECC part, which is composed of aggregate, cement paste, voids, and cracks, is regarded as a continuum and the strain within the element is calculated by interpolating the displacement of grid points. The absolute value of this strain changes depending on the element dimensions, so it is necessary to set the element dimensions according to the purpose. Despite it is in need to select element dimensions carefully, this modeling approach is effective to visualize and understand how different parts of the PVA-ECC material deform under various conditions or loads.

3. Test results and discussions

3.1 Verification of digital image correlation technique

To verify the results obtained from the DIC technique, a beam labeled S-NP-550-E was chosen to compare the results obtained from the conventional measurements. **Fig. 8** shows the locations of the compared seals for analyzing the displacement and strain. During the loading, the displacement and strain were measured by both methods simultaneously. From the analysis results, the load–deflection curves obtained from the LVDT and the DIC technique are presented in **Fig. 9(a)**, which show good agreement. Additionally, as shown in **Fig. 9(b)**, the results of the load-strain relationship can also match well regarding the overall changing tendency. However, there are large variations, such as negative values in the image analysis results of the strain values. This may be caused by the wobbling of the camera and specimen during measurement, which is an issue that should be improved in the future. Even so, the DIC technique can be considered a reliable method for deformation measurement. Due to its sensitivity to the deformation variation, it is possible to have direct observation of shear cracking development via this technique.

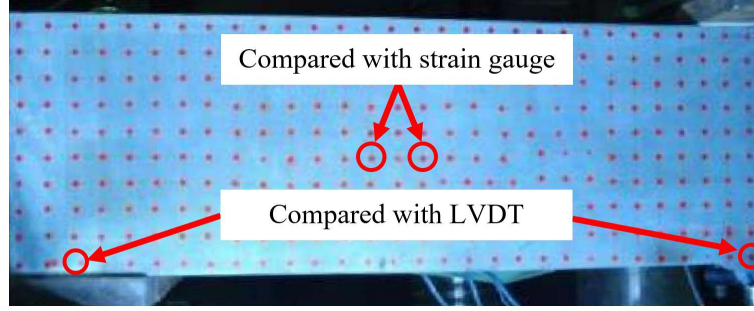


Fig. 8 Compared seals' positions

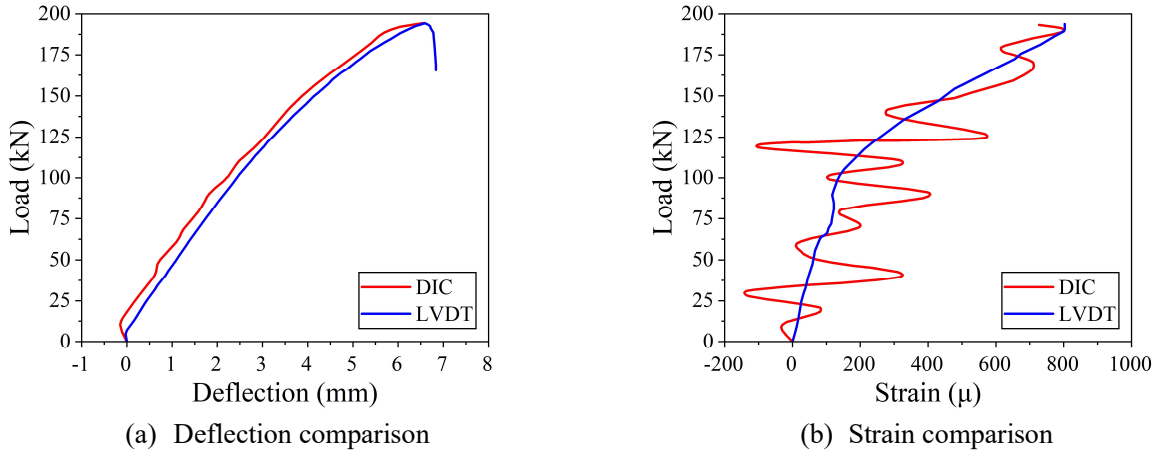


Fig. 9 Comparison between the DIC technique and the conventional method

3.2 Non-precracked beams

The experimental load versus midspan deflection relationships for all series in symmetric and antisymmetric loading tests are shown in **Fig. 10(a-b)** and **Fig. 11(a)**, respectively. Due to an error in the data logger, the load-deflection data of beam NP-550-C was missed from a certain point. The recorded data from the concurrent image data analysis was employed and plotted in the graph to substitute this loss. To observe the effects of the coarse aggregate in improving the performance of the PVA-ECC beams, some parameters were evaluated, including the shear capacity, stiffness, and ductility. The stiffness of beam is described as the index to quantify the capability of the concrete to resist the deformation to the applied loads. Marzouk and Hussein [37] divided the load-deflection curves of concrete specimens that experienced shear failure into two segments: the initial stiffness (K_i) at the onset of loading and secant stiffness (K_s) extending up to the point where tension reinforcement initiated yielding, as shown in **Fig. 12**. Meanwhile, the ductility of the beam was defined as the ratio between the deflection associated with the ultimate load and the deflection corresponding to the initial yielding of flexure reinforcement [37]. The calculated results are presented in **Table 4**.

In the symmetric loading test, without precracks, the differences in the stiffness and ductility of the PVA-ECC beam with (S-NP-550-C) and without coarse aggregate (S-NP-550-E) are insignificant as presented in **Table 4**. However, beam S-NP-550-C has approximately 19.7% lower shear capacity than beam S-NP-550-E due to coarse aggregates that weaken the tensile property of PVA-ECC. The coarse aggregates obstruct fiber bridging on the crack surface since fewer fibers exist in the crack sections occupied by the coarse aggregates. When there are no precracks, the tensile behavior of the beams is more dominant than their shear behavior. This result suits the knowledge that has been obtained from previous researchers [27]. This indicates that, under the fixed stress condition, the shear resistance contributed by the coarse aggregate to the PVA-ECC beam is minimal.

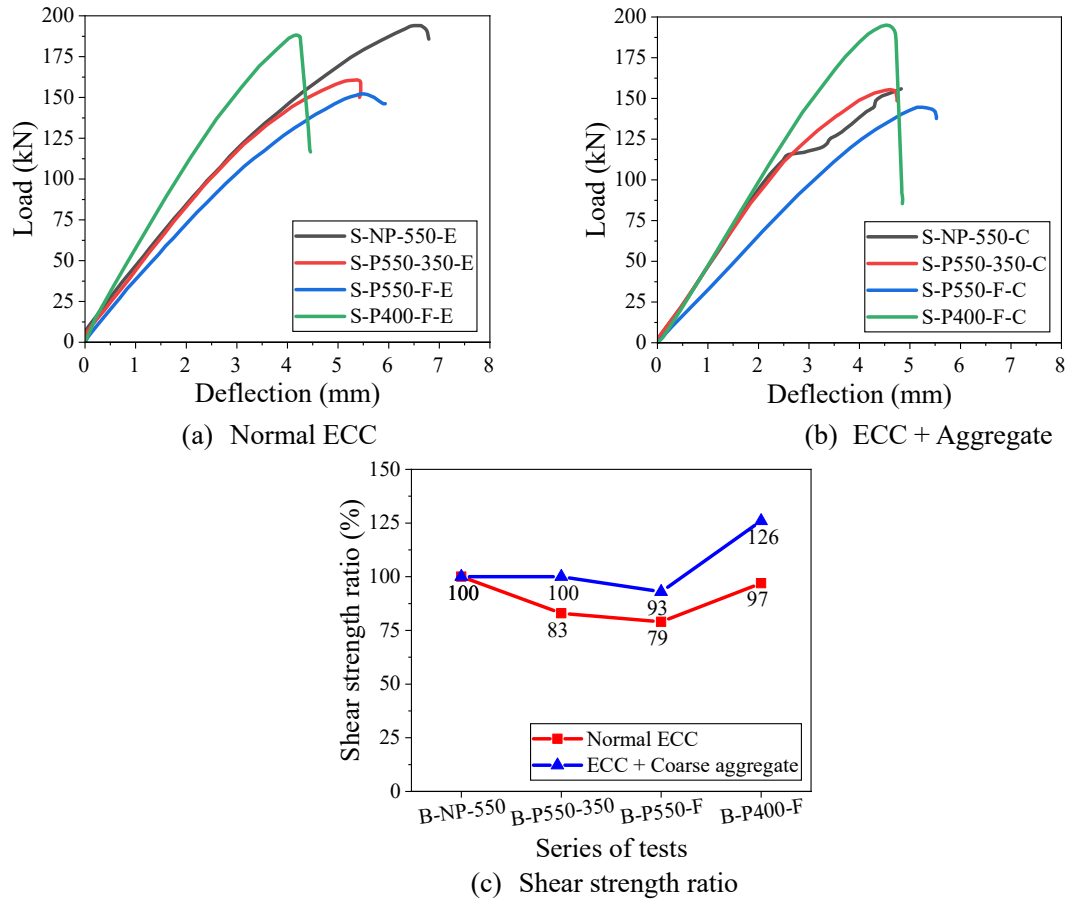


Fig. 10 Symmetric loading tests results

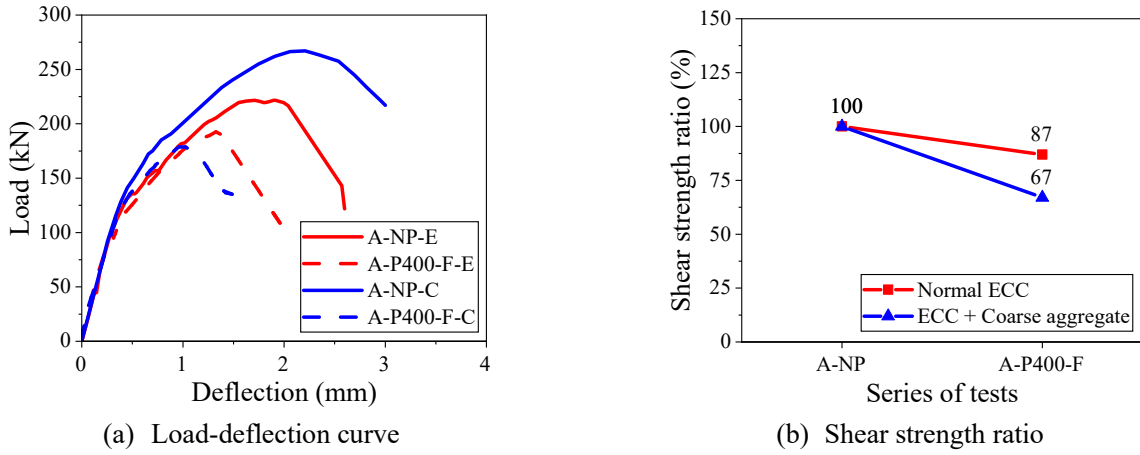


Fig. 11 Antisymmetric loading test results

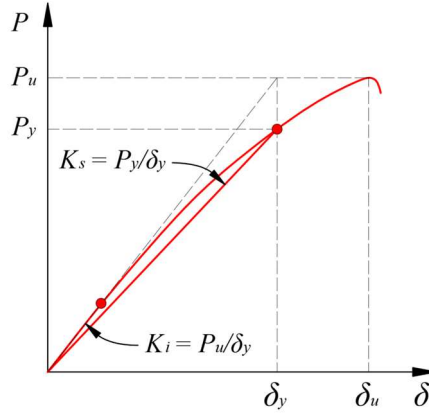


Fig. 12 Stiffness of the beam calculation [37]

Table 4 Results of initial stiffness and ductility of the beam

Specimen	P_y (kN)	P_u (kN)	δ_y (mm)	δ_u (mm)	K_i (kN/mm)	K_s (kN/mm)	DI
S-NP-550-E	164.22	193.97	4.78	6.64	40.55	34.33	1.39
S-NP-550-C	120.35	155.84	3.28	4.83	47.48	36.67	1.47
S-P550-350-E	142.50	160.78	3.99	5.38	40.29	35.71	1.35
S-P550-350-C	136.50	155.41	3.43	4.61	45.31	39.80	1.34
S-P550-F-E	126.72	152.16	3.92	5.52	38.78	32.30	1.39
S-P550-F-C	133.00	144.59	4.40	5.25	32.86	30.23	1.19
S-P400-F-E	169.45	188.28	3.45	4.17	54.57	49.12	1.21
S-P400-F-C	182.00	195.04	3.90	4.53	50.01	46.67	1.16
A-NP-400-E-S	150.69	221.56	0.65	1.71	343.32	233.50	2.65
A-NP-400-C-S	181.00	267.02	0.75	2.21	356.02	241.33	2.94
A-P400-F-E-S	124.00	192.66	0.48	1.33	401.38	258.33	2.76
A-P400-F-C-S	144.30	178.62	0.56	0.96	318.96	257.68	1.71

Note: P_y = yield load; P_u = ultimate load; δ_y = deflection corresponds to the yield load; δ_u = deflection corresponds to the ultimate load; K_i = initial stiffness; K_s = secant stiffness; DI = ductility index $DI = \delta_u/\delta_y$.

In contrast to the beam S-NP-550-C, in the antisymmetric loading test, the shear capacity of the PVA-ECC beam incorporated with coarse aggregate (A-NP-400-C-S) increased by around 20.5% compared to that without coarse aggregate (A-NP-400-E-S), as illustrated in **Fig. 11(a)**. It is clear that the shear capacity of PVA-ECC with coarse aggregate is slightly higher than that of normal PVA-ECC, even though it demonstrated worse flexural properties than normal PVA-ECC (see **Fig. 3**). Meanwhile, they are comparable in the initial stiffness and ductility. It indicates that the contribution of the coarse aggregate effectively enhances the shear capacity but is insignificant to the initial stiffness and ductility of the PVA-ECC beam.

3.3 Precracked beams

3.3.1 Symmetric loading test

The test results of precracked beams in the symmetric loading test are shown in **Fig. 10**. When there is a precrack, the shear capacity, and ductility of both materials have no obvious difference. However, comparing the results of three series (NP-550, P550-350, and P550-F) with a span of 550 mm, for cases with initial damage (under the reproduction of the principal stress axis rotation), the shear strength of normal PVA-ECC beams dropped significantly, whereas the case with coarse aggregate did not show an obvious decrease in load capacity (see **Fig. 10(c)**). The

decreased shear strength ratios were approximately 17% and 21% for the P550-350 and P550-F beams, respectively, while for the beams with coarse aggregate, the dropping shear strength ratios were less than 7% compared to the NP-550 beam. The reason may be attributed to more considerable shear movements under severe stress rotation fields than under non-precracked conditions where pure shear failure occurs. In the complex stress condition, the role of coarse aggregate is clearly illustrated in **Fig. 13**. The crack interface of normal PVA-ECC is smooth and bridges with flexible PVA fibers. Due to the slippage of crack interfaces, the PVA fibers could be partially broken, and the stress transfer will be ineffective. When the coarse aggregate is incorporated, the surface of the crack will be rougher, which can increase the shear resistance at the crack interface. Besides, the presence of coarse aggregates can protect the fibers from damage during the occurrence of cracks. When there was no damage, mixing the coarse aggregate reduced the shear strength under the rotation of the principal stress axis. The shear strength ratio of the PVA-ECC beams incorporated with coarse aggregate does not drop prominently. Also, comparing the beam P550-350-C and the beam P550-350-E, the beam P550-350-C has a slightly higher initial stiffness than the beam P550-350-E. This indicates a robust material even under the rotation of the principal stress axis due to the changes in loading types. Comparing the series of P550-350 and P550-F with different precracked levels, there was little difference in yield strength, which means that the initial damage was serious. In the P550-F series, the precrack was set to almost failure, where the load increase during the test became nearly flat in the load-deflection curve. As a result, no significant difference in the shear capacity, initial stiffness, and ductility was observed for the P550-F series with and without coarse aggregates. Thus, the level of precrack can have prominent effects on the performance of the beam. When the level of precracks is serious, the contribution of the coarse aggregate will be ineffective.

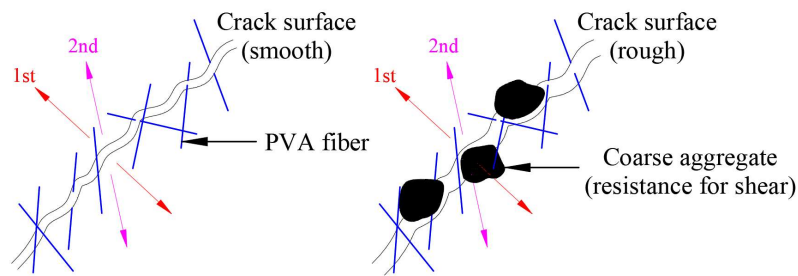


Fig. 13 Images of material behavior on crack

For the P400-F series with a span of 400 mm in the second loading, the shear strength was equal to or higher than that of normal PVA-ECC due to the inclusion of coarse aggregate. Even so, similar to that of the P500-F series, the initial stiffness and ductility of the beams in the P400-F series have no significant difference. Comparing the shear strength ratio of P550-F and P400-F, PVA-ECC with coarse aggregate shows a larger increase in shear strength ratio even under different principal stress axes of rotation angles. The experimental results reveal that the shear strength ratio in both materials with a smaller shear span to depth ratio in the secondary loading ($a/d = 2.29$) is greater than that with a larger shear span to depth ratio ($a/d = 3.14$). Therefore, although the improvement of the PVA-ECC beam is not noticeable, the contribution of the coarse aggregates is excellent in enhancing the shear strength ratio of the PVA-ECC beam.

3.3.2 Antisymmetric loading test

As shown in Fig. 12, the results of precracked beams subjected to the antisymmetric loading test were obtained. In contrast to the result from the P400-F series in the symmetric loading test, the shear strength ratio of P400-F in the antisymmetric loading test with and without coarse aggregate is reduced by approximately 33% and 13%,

respectively (see **Fig. 11(b)**). The ductility decreased by around 10.1% and 3.3% for the PVA-ECC beams with and without coarse aggregate, respectively. The precracks can cause significant degradation of the shear strength ratio for the PVA-ECC beam with both materials. The reduction in shear strength ratio and ductility of the case with precracks is larger than that of a normal PVA-ECC beam. This large capacity reduction might be due to the partial filling of the crack interfaces by the coarse aggregate and the decrease of the bridging stress at the cracks. However, the initial stiffness of the beam P400-F-C-S is significantly increased by around 24.9% compared to that of the beam P400-F-E-S. This indicates that the contribution of the coarse aggregate is preferable in improving the initial stiffness of the PVA-ECC beam in the antisymmetric loading test under complex stress conditions. The effectiveness of the inclusion of coarse aggregate in PVA-ECC beams under antisymmetric loading needs to be further investigated in future studies.

3.4 Cracking behavior

To understand the cracking behavior of the PVA-ECC beams, the crack patterns of beams in the symmetric loading test at the failure stage are shown in **Fig. 14**, and the density and angle of cracks on the failure side are listed in **Table 5**. The crack density on the failure side was defined as the total length of the cracks in the failure side divided by the total area of the failure side. In the case without initial damage (NP-550 series), split cracks occur along the main reinforcing bar. These cracks developed at the same time as shear cracks. For beam NP-550-E, multiple fine diagonal cracks were gradually formed and tended to increase in length and width with a crack density of 0.0452 mm/mm². Some were visible from the beginning, while others only became visible as they grew. These multiple cracks were formed due to the bridging stress at the crack interface contributed by the PVA fibers. In addition, some flexural cracks were also formed along the flexural area. However, the lengths of the flexural cracks were only around 5-20 mm, with a crack density of 0.0038 mm/mm². A normal PVA-ECC beam can hardly distribute the stress evenly to the flexural area of the beam. The number of multiple cracks formed in beam NP-550-C is less than in beam NP-550-E. The coarse aggregate can reduce the distribution of cracks and lead to more continuous cracks. Therefore, the cracks in the PVA-ECC beam incorporated with coarse aggregate are less dense.

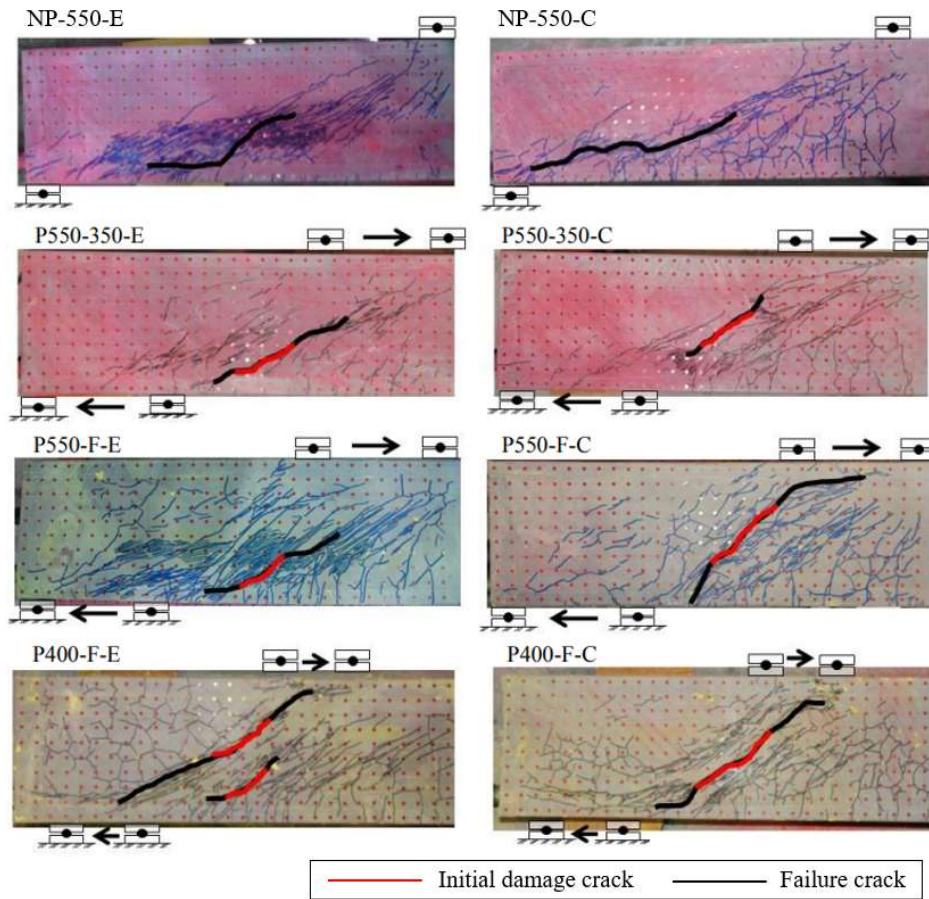


Fig. 14 Crack patterns of all beams

Table 5 Crack density and average crack angle of the specimens

Specimen	Crack Density (mm/mm ²)	Average Crack Angle (°)
S-NP-550-E	0.0490	44.4
S-NP-550-C	0.0478	20.1
S-P550-350-E	0.0261	26.5
S-P550-350-C	0.0373	44.1
S-P550-F-E	0.0801	25.4
S-P550-F-C	0.0542	42.5
S-P400-F-E	0.0595	32.1
S-P400-F-C	0.0557	40.9

The phenomenon is very different for the cases with initial damage (P550-350, P550-F, P400-F). The precracks propagated to supporting and loading plates, and the main diagonal crack became distinguishable among these inclined cracks. It causes significant differences in the overall crack patterns of the beams. In addition, there are higher amounts of multiple fine cracks in the normal PVA-ECC beam than in the case with coarse aggregate. The crack dispersibility is reduced by the coarse aggregate, as discussed in the previous section [28].

As shown in **Fig. 14**, for the specimen P550-350-E with an initial loading of 350 kN, it was difficult to observe fine cracks due to its rough surface, but it was considered that there were many multiple cracks as in other cases. The initial crack produced by the first loading is indicated by a red line with a length of 95 mm and a crack angle of around 26°. In the second loading, the initial major crack developed and propagated with a total length of 210 mm, and the crack angle was not changed. Multiple fine cracks were produced parallel to the initial crack with a short

length. Some flexural cracks also appeared in a small number with a length of around 3-26 mm. In contrast, for beam P550-350-C, the position of the initial crack was slightly higher than that on beam P550-350-E. Due to the presence of coarse aggregate, the crack angle was almost double that occurred on beam P550-350-E at approximately 44° with a length of 88 mm. Then, in the second loading, the major crack propagated to 140 mm with the same crack angle. Multiple cracks were also produced parallel to the major crack. Compared to the beam P550-350-E, these multiple cracks were longer and less dense. The flexural cracks were also longer than that on beam P550-350-E, ranging from 6 to 121 mm. Owing to the effects of the coarse aggregate, the secondary cracks were arrested by the precracks and resulted in patterns with more continuous cracks.

When the initial loading increased to 458 kN, beam P550-F-E had a similar initial crack as beam P550-350-E. Due to the higher load level, more multiple fine cracks were observed parallel to the initial crack. In the second loading, the initial crack tended to propagate to the loading and support plate with a length of 203 mm, and many new cracks appeared. Similar to beam P550-350-C, the position of the initial crack formed on beam P550-F-C was higher than that on beam P550-F-E with a length of 121 mm and crack angle of 43° . However, during the second loading, the initial crack propagated in different directions and tended to propagate to the loading plate with a length of 313 mm. Even so, multiple cracks were formed but with less density, which could be attributed to the lower bridging stress at the crack interface.

For beam P400-F-E, two initial cracks were produced with a length of 69 and 95 mm, and they were formed in parallel with the crack angle and spacing of about 32° and 54 mm, respectively. In the second loading, one of these two initial cracks increased in length significantly to approximately 309 mm, while the other one was only around 117 mm. Also, several flexural cracks appeared with a total crack density of 0.06 mm/mm^2 . In contrast to the P550 series, the secondary cracks formed in P400-F-E were somewhat orthogonal to the initial cracks. This indicates that the in-plane stress was perpendicular to the precracks, which is not beneficial to the shear resistance. Also, the discontinuous secondary crack patterns imply that the uncracked regions act independently in resisting stress due to the negligible shear contribution from the PVA fibers. On the other hand, for beam P400-F-C, only a single major crack was initially formed. The initial crack length was around 131 mm, with a crack angle of approximately 41° . The mechanism of secondary cracks formed on beam P400-F-C was similar to that on beam P400-F-E. However, these orthogonal cracks were much less than those of the beam P400-F-E, and the secondary cracks tended to be more continuous due to the great contribution from the coarse aggregates. In this case, the opening and sliding of the precracks were limited, and the shear resistance was largely improved.

From the DIC technique, the shear strain distribution results are extracted and presented in the contour diagram, as shown in **Fig. 15**. Only the contour diagram of beams P400-F-E and P400-F-C are provided as they are typical results and can show common phenomena. For the secondary loading, three stages of loading (at 80 kN, 160 kN, and peak load) were selected for discussion purposes. The vertical displacement in the contour diagram is multiplied by five times. As observed, the crack patterns of the P400-F series were accurately captured as shear strain. With the precrack level of 469 kN, the shear strains were distributed locally at the middle of the beam, producing two inclined initial cracks. When the coarse aggregates were incorporated, the shear strain distribution was almost similar to that without coarse aggregate, and there was no clear difference in the mid-span displacement between these beams. However, only one major crack was formed in the case with coarse aggregates, even with a higher level of initial loading (489 kN). During the early stage of the second loading (80 kN), the shear strain distribution was comparable to that under the initial damage condition. When the load reached 160 kN, these localized strains become more prominent as the propagation of the cracks. At this stage, the area of strain distribution had not much changed. As the load increased, a significant strain development was observed in beam P400-F-E, resulting from the crack opening and formation of tangible cracks. However, for beam P400-F-C, the shear strain level is not as high as that in beam P400-F-C-E due to the inclusion of the coarse aggregates. Therefore, the contribution of the coarse aggregates in

enhancing the shear capacity of the PVA-ECC beams can be directly observed via the DIC technique.

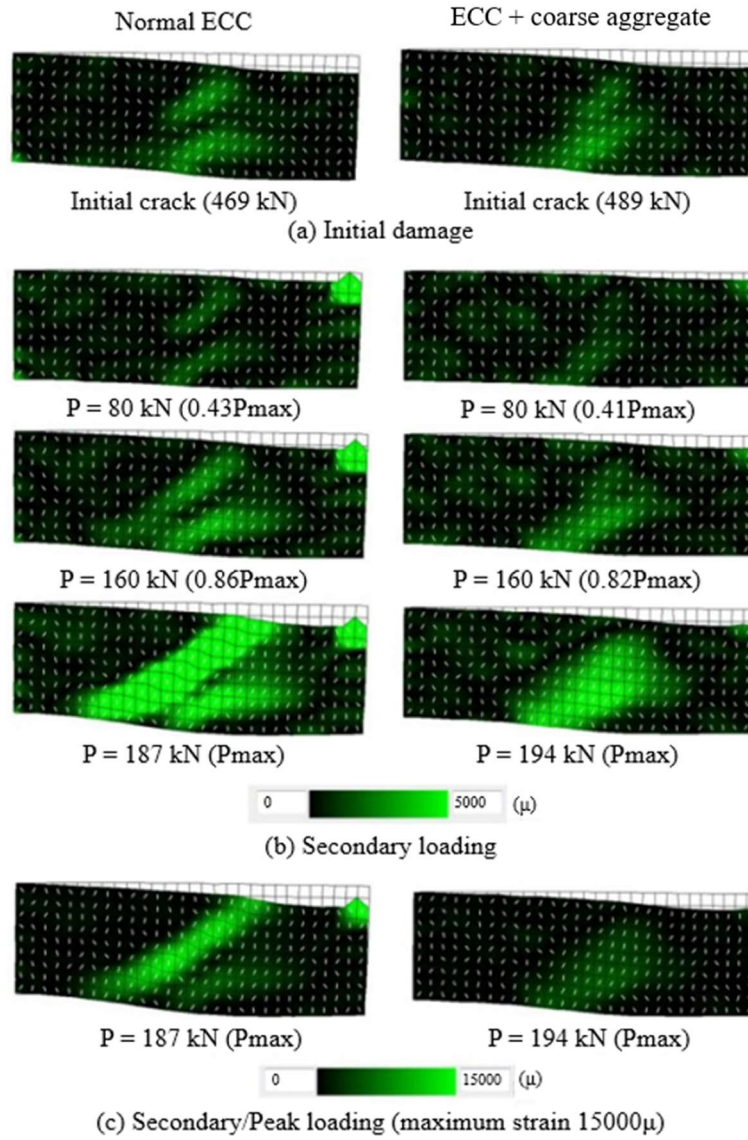


Fig. 15 Shear strain contour

3.5 Crack opening and sliding

The strain contours in crack opening and sliding of the P400-F series are given in **Fig. 16**. The strain that increases perpendicular and parallel to the crack surface indicates the crack opening and sliding process, respectively. The red-colored contours represent the crack opening, while the blue-colored contours represent the crack sliding in the whole range of the subjected area. A certain principal strain value (5000 μ in this case) is used as a reference value. The cracks extend in each element when the principal strain reaches that value as the loading progresses. The white lines indicate the angle of failure crack in each block of elements, and the length of these lines is proportional to the value of strain of each element.

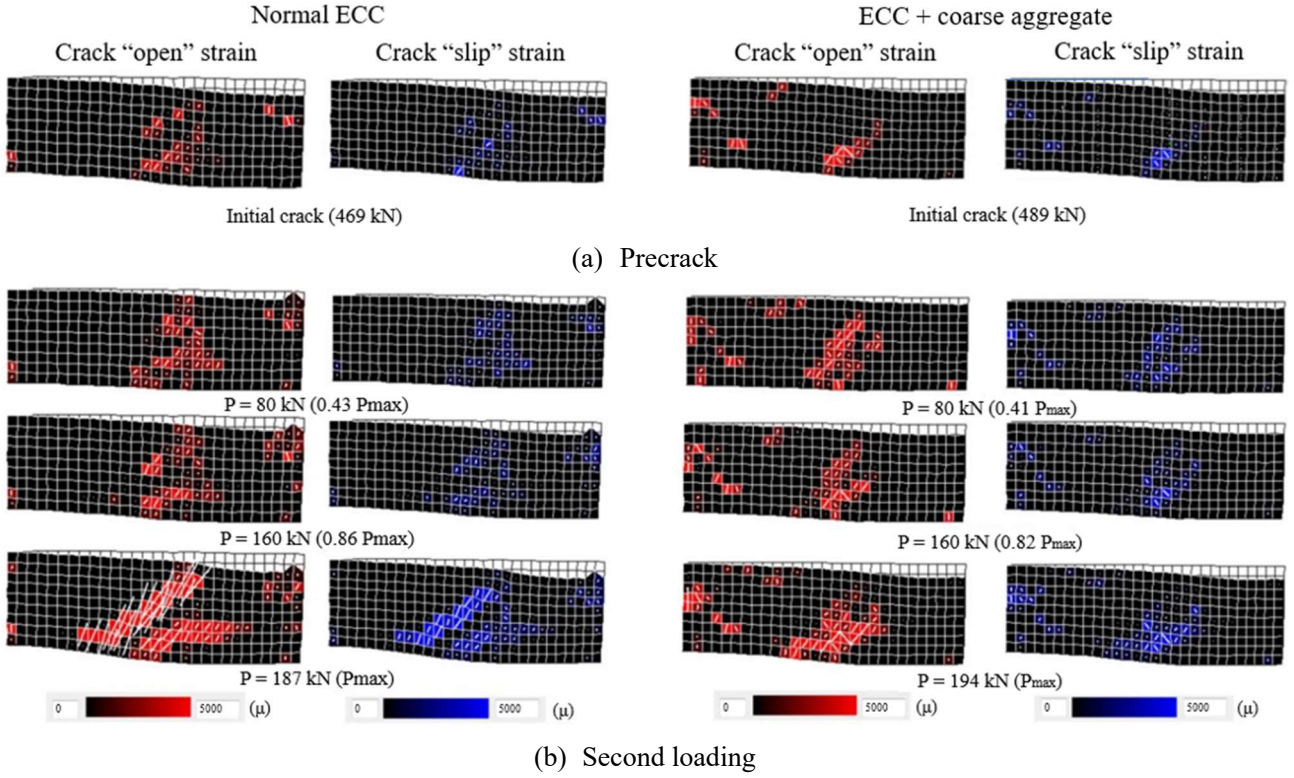


Fig. 16 Strain behavior due to opening and sliding of cracks

Regarding the crack opening and sliding, the shear crack mechanism was revealed cautiously using the DIC technique. In the initial loading stage, the crack width that occurred in the normal PVA-ECC was slightly smaller than in the case incorporated with the coarse aggregates. When the load reached 80 kN in the second loading, the crack opening had no obvious progress, while the crack sliding developed significantly. Since the coarse aggregate in the PVA-ECC beams makes the cracked surface rougher, the interlocking of PVA-ECC and coarse aggregate occurred. This prevented the sudden drop of load and enhanced the residual shear resistance of the beam after initial loading. Comparing the magnitude of crack extension between materials in the peak loading stage, the crack opening and sliding in normal PVA-ECC developed more significantly. Hence, it could be confirmed that the PVA-ECC with coarse aggregate had significantly suppressed the crack opening and sliding and finally improved the shear performance of the beam.

The strains at the opening and sliding of cracks calculated based on the lattice (both near the center of the fracture surface) are shown in **Fig. 17**. The element with the highest strain in the specimen was selected for the calculated area. In the initial condition of the loading process, there is an insignificant difference between the two materials. However, when the load reached around 130 kN, the normal PVA-ECC opening and sliding values became higher than that of PVA-ECC with coarse aggregates. At the peak loading condition, the strains on opening and sliding of the PVA-ECC were suppressed by approximately 1300 μ and 2700 μ , respectively, due to the contribution of the coarse aggregates. The decrease in crack sliding was larger than that in the crack opening because the coarse aggregate enhanced the shear resistance more evident than the tensile resistance. Therefore, the positive effects of the coarse aggregate in reducing the crack opening and sliding of the PVA-ECC beam are quantitatively confirmed.

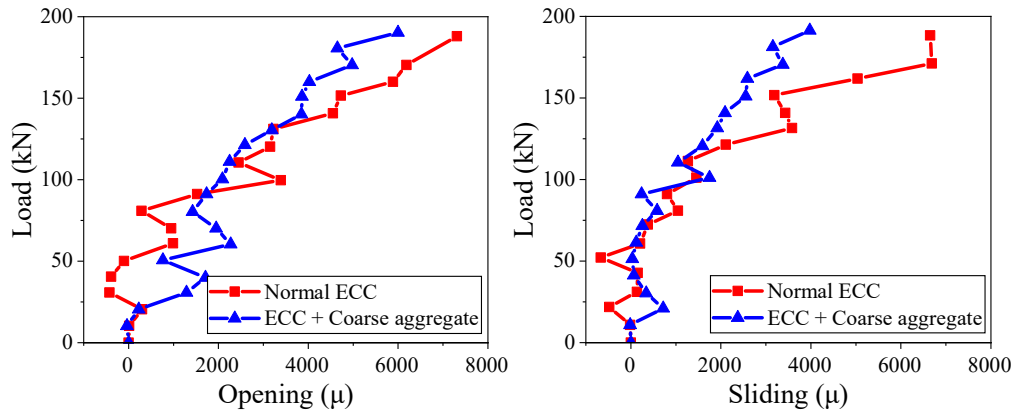


Fig. 17 Strain development with opening and sliding of cracks at the local scale

4. Conclusions

In this paper, an experimental study on the shear cracking behavior of pre-damaged PVA-aggregate mixed ECC beams was performed under the rotation of the principal stress axis. When the principal stress direction changes, new cracks form nearly orthogonal to the pre-existing cracks, largely affecting the stress transfer around the precracks. To reveal the cracking mechanism, the DIC technique was adopted to monitor the crack opening and sliding during the loading directly. From the results and discussions, the following conclusions can be reached:

- (1) The displacement and strain distribution of the PVA-ECC beams were cautiously observed using the DIC technique. The results of this technique were validated with the conventional measurement, which shows a good agreement. The DIC technique is reliable for monitoring the shear cracking mechanisms of the PVA-ECC beams with and without coarse aggregates under complex stress conditions.
- (2) The performance improvement of the PVA-ECC beams can be attained if the level of the precracks is 350 kN. However, when the initial damage becomes more serious, it can cause severe degradation of the shear strength ratio of the PVA-ECC beams. Due to the reopening and direction changing of the initial cracks during the second loading, shear stress could be much higher, resulting in severe cracking.
- (3) The positive effects of the coarse aggregates in enhancing the shear performance of the PVA-ECC beams were revealed, especially under complex stress conditions. The coarse aggregates can increase the roughness of the crack surface and protect the PVA fibers from damage during the occurrence of cracks. By including the coarse aggregates, the degradation of the shear strength ratio of the PVA-ECC beam due to the initial damage is much smaller than that without coarse aggregate. Besides, the initial stiffness of the beam can also be improved significantly.
- (4) It was revealed that the addition of coarse aggregate suppressed the displacement behavior by measuring the width of the "opening" and "sliding" of the surface cracks on a contour diagram. With the shear span of 400 mm in the second loading and the level of precrack set to almost failure, the strains at opening and sliding of the PVA-ECC beam can be reduced significantly to approximately 1300 μ and 2700 μ , respectively. The reduction in crack sliding was much higher than that in the crack opening, as the coarse aggregate improved the shear resistance more than the tensile resistance.

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