Axial compressive behavior of engineered cementitious composite confined by fiber-reinforced polymer

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ABSTRACT

A novel hybrid member made from two kinds of composite materials, ductile engineered cementitious composite (ECC) as the core material and linear elastic fiber-reinforced polymer (FRP) as the confining material was proposed for application. A series of axial compressive experiments on FRP-confined ECC cylinders were carried out. The test results indicated that FRP-confined ECC specimens exhibited similar compression hardening behavior in the axial stress-strain curve to FRP-confined normal concrete specimens. Moreover, the “self-confinement” effect of ECC and the confinement stiffness of FRP had significant influence on the stress-strain response and failure mode. Based on the FRP strain distribution, a failure mechanism was proposed for FRP-confined cement-based materials under compression. FRP-confined ECC cylinders underwent three distinct stages under compression: formation of microcracks, formation of multiple cracks, and formation and propagation of major cracks. A qualitative model for FRP confined ECC was developed, which illustrates the effects of different tensile properties of cement-based materials on the failure mode and explains why the hoop rupture strain is lower than the ultimate tensile strain of FRP. In addition, fitting equations were proposed for predicting the compressive strength and ultimate strain of FRP-confined ECC cylinders at the ultimate state.

1. Introduction

Normal concrete (NC) is a typical brittle material with a tensile strain softening behavior, as illustrated by curve (a) in Fig. 1. This inherent material defect causes a common cracking problem in reinforced concrete members, which leads to stress concentration in the reinforcing bars and concrete matrix at the crack location due to strain incompatibility at the concrete-to-rebar interface [1,2]. The consequent bond splitting and spalling of concrete result in only part of the concrete section engaging in the inelastic deformation process of reinforced concrete members, which reduces the integrity and energy dissipation capacity of reinforced concrete members.

To enhance the toughness of normal concrete, a ductile material named engineered cementitious composite (ECC) [3] was developed. ECC is a cement-based mortar-like material reinforced with short randomly distributed polymer fibers. Polyvinyl alcohol (PVA) fibers, which have high tensile strength, high elastic modulus and fine interfacial properties with cement mortar, were extensively used as fiber reinforcement in ECC. When properly designed and processed, PVA-ECC shows a pseudo-strain hardening behavior in tension with much higher tensile strain capacity than normal concrete, as illustrated by curve (b) in Fig. 1. The ductile behavior also improves the deformation compatibility between steel reinforcement and ECC, leading to enhanced performance of reinforced ECC structural members [1,2].

As ECC has been proven to be much tougher than NC, it has been applied to structural repairs and seismic strengthening [4,5]. However, when the region to be strengthened is the potential plastic hinge zone of vertical lateral force resisting members, such as that of piers or columns [6–8], ECC will be subjected to axial compressive load, which is likely to lead to ECC crushing and failure of the structural member. Moreover, the compressive strength and plastic deformation ability of ECC are not high enough. Therefore, it is necessary to enhance the compressive properties of ECC in practical engineering. Usually, the compressive failure of ECC is characterized by a compression softening behavior [9] similar to that of NC, as illustrated by curve (c) in Fig. 1. Nevertheless, the axial strength and deformability of ECC under compression could be enhanced by applying lateral confinement [10]. At present, steel [11] and fiber-reinforced polymer (FRP) [12] are usually used as lateral confinement material for concrete in civil engineering applications. Conventional steel tubes or transverse reinforcements improve the...
strength and ductility of NC [13,14] or ECC [15] under compression, but did not change the compression softening behavior, as illustrated by curve (d) in Fig. 1. On the contrary, the lateral confinement pressure provided by an FRP tube or wrapped FRP jacket continually increases under lateral expansion due to the linear elastic behavior of FRP. As a result, such lateral confinement totally alters the compressive behavior of NC and leads to a compression hardening behavior [16,17], as illustrated by curve (e) in Fig. 1. It is hypothesized that the compressive deformation characteristics induced by FRP confinement are also applicable to ECC. Then the combined unique tensile and compressive properties of FRP-confined ECC are of great potential in optimizing and improving the performance of structural members. Consequently, it is necessary to experimentally validate this hypothesis and to investigate the interactions between FRP and ECC in such configurations.

To date, experimental studies on FRP-confined concrete have been widely conducted, and many analytical models have been proposed to predict its compressive stress-strain response [18–20]. However, to the best of our knowledge, there are no tests on FRP-confined ECC reported in the literature. To fill this knowledge gap, in this study, monotonic and cyclic axial compression tests were conducted on FRP-confined ECC and NC cylinder specimens. To provide different levels of confinement stiffness, two types of FRP, glass FRP (GFRP) and carbon FRP (CFRP), were used. Based on the axial compressive behavior and failure modes of the specimens, the failure mechanisms of FRP-confined ECC were elucidated, and the equations for predicting the ultimate axial strain and the compressive strength of FRP-confined ECC cylinders were established.

2. Experimental program

2.1. Test specimens

In total, 32 cylindrical specimens with diameter of 100 mm and height of 200 mm were prepared and tested in this study, including 8 unconfined (U) and 24 FRP-confined cylinders. Test specimens were divided into two groups: NC (group N) and ECC (group E). For FRP-confined specimens, unidirectional glass fiber sheets (G) or carbon fiber sheets (C) impregnated with epoxy resin were used to wrap the cylinders in the hoop direction. The number of layers varied between 2, 5 and 8 among specimens. In each case, half of the specimens were tested under monotonic (M) loading and others were tested under cyclic (C) loading. Two identical specimens were tested for the unconfined cylinders, and only one specimen in each type was tested for FRP-confined cylinders. A detailed test matrix is shown in Table 1.

The mixture proportions of NC and ECC are shown in Table 2. The cement-based materials were produced with P.O. 42.5 ordinary Portland cement, fly ash with calcium oxide (CaO) content of less than 5% (by weight), silica fume with an average particle size of 0.1–0.3 μm, and quartz sand with a maximum particle size of 0.42 mm as fine aggregate. NC contained gravel with a maximum diameter of 20 mm as coarse aggregate (Fig. 2). ECC does not contain any coarse aggregate, instead, 2% volume fraction of short PVA fibers (Fig. 2) were used. The properties of the PVA fibers are listed in Table 3. The mixed water was common domestic water, and the water-cementitious material ratios of ECC and NC were 0.27 and 0.32, respectively. A polycarboxylate superplasticizer with a solid content of 20% was used as a high-range water-reducing admixture to achieve proper workability.

After casting, both NC and ECC were kept in the molds, covered with plastic sheets, and stored at 20 °C for 24 hrs. Then, the cylinders were maintained under standard curing conditions following the relevant Chinese standard [21] for 28 days in the laboratory under a constant temperature of 20 ± 2 °C and relative humidity of greater than 95%. Afterwards, continuous fiber sheets impregnated with epoxy resin were wrapped onto each cylinder in a wet lay-up process for all confined specimens. The fiber sheets were oriented along the hoop direction perpendicular to the cylinder axis. To ensure adequate bond and continuity of the FRP jacket, an overlap length of 100 mm was included for all wrapped specimens, which corresponds to the central angle of 114.6 degrees. Both ends of the confined specimens were strengthened by an additional FRP strip with a width of 25 mm to avoid local end crushing of NC and ECC. The number of layers of the strengthening strips was kept the same as that of the fiber sheets. All of the FRP-confined specimens were allowed to cure for at least seven days before testing. The age of NC and ECC at testing is 90 days.
2.2. Material properties

2.2.1. ECC

The tensile properties of ECC were determined with uniaxial tension tests on three coupons with cross-sectional dimensions of 20 mm × 100 mm and lengths of 200 mm [22]. The tensile loading was applied at a displacement rate of 0.15 mm/min. Axial strain in tension was measured by a pair of extensometers with gauge lengths of 50 mm. Tensile stress-strain curves of the ECC coupons are plotted in Fig. 3. The ECC exhibited a ductile tensile behavior. The average ultimate tensile strain ($\varepsilon_{tu}$) is determined to be 0.72%. The ultimate tensile strain corresponds to the onset of strain softening in tension, in which the tensile stress decreases until it is lower than the cracking strength ($f_{cr}$). The cube compressive strength ($f_{cu}$) of the ECC obtained from three cube specimens with side length of 100 mm was 73.7 ± 1.1 MPa.

2.2.2. FRP

Tensile tests of FRP flat coupons were conducted in accordance with ASTM D3039 [23] and GB/T 3354-1999 [24]. The nominal width and length of the FRP flat coupons were 25 mm and 230 mm, respectively. The flat coupons were made of five layers of FRP sheets. Aluminum tabs with a width of 25 mm and a length of 50 mm were bonded at both ends of each FRP flat coupon to transfer the forces during the tensile tests. The tensile tests were conducted at a constant displacement rate of 2 mm/min. The axial strains were measured by unidirectional strain gauges (SGs) installed at mid-length on both sides of the coupon. The gauge length of the strain gauges was 15 mm. The tensile strength and elastic modulus of the coupons were calculated according to the nominal thickness [25]. The tensile properties of the FRP flat coupons are listed in Table 4.

2.3. Test setup and loading

The compression tests were conducted on a testing machine with a capacity of 5000 kN. Both monotonic and cyclic loading were carried out in the same force-displacement controlled manner. During axial compression, the load was initially applied at a rate of 2 kN/s. After the axial displacement reached the peak strength displacement, the load was applied at a constant displacement rate of 1 mm/min until compressive failure. The peak strength displacement mentioned here was the axial displacement corresponding to the compressive strength of the unconfined cement-based cylinders. The cyclic loading tests were performed under displacement control at a constant rate of 1 mm/min after reaching peak strength displacement. During the cyclic tests, the peak strength displacement was served as a constant displacement increment for each cycle. Each specimen was first loaded to a specified axial displacement level, which is an integer multiple of the peak strength displacement, then unloaded to a target load level (approximate to the value of 0 kN), and finally reloaded to the next specified displacement level. At each specified displacement level, only one unloading-reloading cycle was employed.

The instrumentation and strain gauge layout are shown in Fig. 4. The axial strain of the specimens was measured with four linear variable displacement transformers (LVDTs) attached to the middle portion of the specimens via a steel frame spaced 90 degrees along the circumference of the cylinders. The gauge length of the LVDTs was 150 mm in the longitudinal direction. Unidirectional strain gauges were spaced equally at mid-height around the circumference of the cylinders to measure the axial strain and hoop strain. For unconfined cylinders, two axial strain gauges (A-SGs) and two lateral strain gauges (L-SGs) with the same gauge length of 50 mm were placed on the surface of the NC and ECC. For FRP-confined cylinders, two A-SGs and four L-SGs with the same gauge length of 15 mm were placed on the surface of the

![Fig. 2. Coarse aggregates and PVA fibers.](image)

![Fig. 3. Uniaxial tensile stress-strain curves of the ECC coupons.](image)

### Table 3

<table>
<thead>
<tr>
<th>Type of fiber</th>
<th>Section</th>
<th>Diameter (µm)</th>
<th>Length (mm)</th>
<th>Elastic modulus (GPa)</th>
<th>Elongation (%)</th>
<th>Tensile strength (MPa)</th>
<th>Density (g/cm³)</th>
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<tr>
<td>PVA</td>
<td>Round</td>
<td>40</td>
<td>12</td>
<td>41</td>
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<td>1560</td>
<td>1.3</td>
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Table 4
Measured tensile properties of the FRP flat coupons.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Number of specimens</th>
<th>Number of FRP layers</th>
<th>Nominal thickness per layer (mm)</th>
<th>Elastic modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Ultimate tensile strain (%)</th>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Standard deviation</td>
<td>Average</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFRP coupon</td>
<td>6</td>
<td>5</td>
<td>0.169</td>
<td>91.1</td>
<td>2.2</td>
<td>2413#</td>
</tr>
<tr>
<td>CFRP coupon</td>
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<td>5</td>
<td>0.111</td>
<td>236.9</td>
<td>10.4</td>
<td>4353</td>
</tr>
</tbody>
</table>

* Since the aluminum tabs at the end of the two coupons slipped at failure, the tensile strength and ultimate tensile strain of the GFRP flat coupons were determined by the average value of the other four coupons.

FRP jackets.

3. Test results

3.1. Axial stress-strain response

In the following sections, the axial stress–strain curves measured under monotonic and cyclic compression for NC and ECC cylinders are plotted in Figs. 5 and 6, respectively. Because of the limited number of specimens, the two loading modes were mainly used to verify the repeatability of the test results. The compressive behaviors of NC and ECC with and without FRP confinement were compared, and the effects of both GFRP and CFRP jackets on the compressive behavior with different confinement levels were demonstrated.

Figs. 5a, b and 6a,b show that for unconfined cylinders, the axial stress-strain curves of NC and ECC exhibit ascending branch as the strain increases during the process of elastic deformation and a post-peak descending branch due to crushing. However, one of the differences between NC and ECC is that the elastic modulus ($E_c$) of ECC is approximately 2/3 of that of NC, and the Poisson’s ratio of ECC ($\nu_c = 0.24$) is slightly larger than that of NC ($\nu_c = 0.20$) due to the absence of coarse aggregates. Another difference was observed in the descending stage. NC exhibited an obvious brittle behavior in which there was almost no residual strength after the peak strength, whereas ECC exhibited a certain ductile deformation capacity in which the compressive stress decreased gradually with increasing strain.

However, as far as ductility is concerned, the axial strain corresponding to the peak strength for unconfined ECC under axial compression is considerably less than the strain capacity of ECC in axial tension.

The test results of unconfined NC and ECC cylinders under monotonic and cyclic compression are summarized in Table 5. The elastic modulus ($E_c$), Poisson’s ratio ($\nu_c$), and axial strain ($\varepsilon_c$) corresponding to the peak strength for the unconfined cement-based material were calculated from the strain gauge data [26,27]. The compressive strength ($f'_c$) and the corresponding axial strain ($\varepsilon_c$) of NC and ECC used later in this research refer to the test results obtained under monotonic loading.

In addition, as shown in Fig. 5c–h and 6c–h, the axial stress-strain curves of FRP-confined NC and ECC cylinders have some similar features and differences:

1) Similar to the NC specimens, the ECC cylinders wrapped by FRP jackets exhibited compression hardening behavior as indicated by the second ascending branch of the axial stress-strain curve.
2) When the numbers of wrapped FRP layers were few (i.e., lower confinement stiffness), the axial stress decreased slightly after the end of first ascending branch (which was determined as the yield point of axial compressive behavior by the farthest point method [28,29]) before increased again. Particularly, this phenomenon was more obvious for ECC specimens (e.g., E-G2-M and E-C2-M) than for NC specimens. The phenomenon disappeared with increasing confinement stiffness. The reason will be explained in section 3.3.
3) In most cases, failure of FRP-confined NC or ECC cylinders was very

Fig. 4. Instrumentation and strain gauge layout.
sudden with a sharp drop in the compressive bearing capacity upon the rupture of FRP. However, for ECC cylinders with lower FRP confinement stiffness (i.e., specimens E-G2-M/C shown in Fig. 6c and E-C2-M/C shown in Fig. 6d), the post-peak normal stress in the axial stress-strain curves decreased slowly. This behavior was mainly related to the fact that the axial stress at failure (FRP rupture) was not much higher than that of the compressive strength of the unconfined cylinder. Additionally, the short fibers uniformly distributed in the ECC matrix can control the development of splitting cracks so that the confined ECC core crushed gradually.

4) The axial stress-strain curves of confined specimens under monotonic loading were close to the skeleton curve of those under cyclic.
loading. Furthermore, the specimen failure occurred later in most cyclic tests than their monotonically loaded counterparts. Hence, the confined specimens under cyclic loading tended to achieve larger ultimate axial strain and strength. A similar phenomenon was also found by Lam et al. [30]. This might be attributed to that the cracks in NC and ECC were more fully developed under cyclic loading, which led to more uniform distribution of lateral strain in the FRP jackets.

5) Pinching behavior could obviously be observed in the cyclic axial stress-strain curves. This phenomenon inferred that the samples underwent a compaction process during reloading cycles due to the crushing of NC and ECC. It was noted that the pinching phenomenon

Fig. 6. Axial stress-strain curves of ECC cylinders under monotonic and cyclic loading.
of the NC specimens occurred at approximately 1% of axial strain, whereas that of the ECC specimens occurred later (approximately 3% of the axial strain).

### 3.2. Experimental observations and failure modes

For the unconfined NC cylinders under axial compression, several typical vertical splitting cracks were formed in the cylinders and eventually caused NC to crush due to the principal tensile strain, as shown in Fig. 7a. Meanwhile, a conical failure surface (the dotted line plotted in Fig. 7a) was formed at both ends of the NC cylinders because of the friction between the specimen ends and load plates, which is not the inherent compressive property of NC cylinders but a special test phenomenon under the specific test conditions. For the unconfined ECC cylinders, owing to the “self-confinement” effect of ECC generated by fiber reinforcement [1], the lateral expansion of the cylinder was restrained. The cylinder was equivalent to being slightly laterally confined. As a result, several inclined cracks were formed at failure, as shown in Fig. 7a.

For the FRP-confined NC and ECC cylinders, the final failure of all the specimens was caused by the rupture of the FRP jackets. Moreover, as both ends of the FRP-confined cylinders were strengthened by additional FRP strips, the rupture of the FRP jackets occurred mostly at the mid-height of the specimens. All FRP ruptures occurred outside the overlap zone of the FRP sheets, and there was no obvious bonding failure in the overlap zone. After the FRP jackets ruptured, most of the NC was crushed and splashed, whereas the ECC was crushed locally with no splashing.

Fig. 7b shows the evolution of typical failure modes of confined NC and ECC specimens under monotonic loadings with increasing numbers of confining FRP sheets, in which the wrapped FRP jackets were removed. For the FRP-confined NC cylinders, the cracks in concrete under triaxial compression were fully developed. There was no significant difference in the size of broken pieces in concrete as the number of FRP layers increased. However, for the FRP-confined ECC cylinders, the number of major cracks in ECC increased while the spacing of major cracks decreased as the number of FRP layers increased. Therefore, this difference was indicated to be related to both the fibers reinforcement in the ECC and the confinement levels of the FRP jackets.

### 3.3. Stress-strain relationships

The axial stress versus axial and lateral strain curves of the FRP-confined NC and ECC cylinders under monotonic compression are plotted in Fig. 8, and the obtained important performance characteristics of these cylinders are listed in Table 6. The lateral strain (\(\varepsilon_l\)) is determined by averaging the data of the three L-SGs outside the overlapping zone (L-SG2 ~ L-SG4 shown in Fig. 4) for the FRP-confined cylinders [31]. Since one of the L-SGs of the FRP-confined specimens was damaged during expansion, a part of the test results is plotted as a dotted line in Fig. 8.

For the specimens with the same type of FRP, the NC and ECC cylinders have the following characteristics in common: 1) The ultimate compressive strength (\(f'_c\)), ultimate axial strain (\(\varepsilon_{cu}\)) and the hoop rupture strain (\(\varepsilon_{h,rupt}\)) of the specimens increased with increases in the actual confinement ratio (\(\rho_f\)) or the confinement stiffness ratio (\(\rho_K\)).

### Table 5

Test results of unconfined NC and ECC cylinders under monotonic and cyclic compression.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>(f'_c) (MPa)</th>
<th>(\varepsilon_{cu}) ((\mu\varepsilon))</th>
<th>(E_c) (GPa)</th>
<th>(\nu_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Average</td>
<td>Measured</td>
<td>Average</td>
</tr>
<tr>
<td>N-U-M</td>
<td>83.3</td>
<td>79.7</td>
<td>2498</td>
<td>2525</td>
</tr>
<tr>
<td></td>
<td>76.1</td>
<td>2551</td>
<td>33.4</td>
<td>29.9</td>
</tr>
<tr>
<td>N-U-C</td>
<td>64.6</td>
<td>70.6</td>
<td>2221</td>
<td>2481</td>
</tr>
<tr>
<td>E-U-M</td>
<td>64.7</td>
<td>64.6</td>
<td>3998</td>
<td>3535</td>
</tr>
<tr>
<td></td>
<td>64.5</td>
<td>3071</td>
<td>23.3</td>
<td>25.3</td>
</tr>
<tr>
<td>E-U-C</td>
<td>64.8</td>
<td>66.0</td>
<td>3978</td>
<td>3579</td>
</tr>
<tr>
<td></td>
<td>67.1</td>
<td>3180</td>
<td>24.7</td>
<td>24.7</td>
</tr>
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</table>

Fig. 7b. Typical failure modes of NC and ECC cylinders.
corresponding to the yield point on the axial stress-strain curve was larger than the compressive strength of the unconfined NC or ECC materials, and the strength enhancement increased with increasing FRP confinement levels. However, there were also differences between the behavior of NC and ECC specimens. According to the test results shown in Fig. 9, for unconfined specimens, the axial stress of ECC is smaller than that of NC under the same axial strain, but the lateral strain is larger. These differences were mainly due to the lower elastic modulus and higher Poisson’s ratio of ECC.

Comparing to NC specimens, ECC exhibited a more obvious decrease in axial stress near the yield point of the axial stress-strain curve for FRP-confined cylinders. It could be explained well by the lateral strain rate ($\varepsilon_{lc}$) shown in Fig. 10. Axial strain and lateral strain in the figure were normalized by their own axial strain ($\varepsilon_{co}$) corresponding to peak strength of unconfined NC and ECC, and the slope of the curve was the growth rate of the lateral strain with the axial strain. Fig. 10 showed that the lateral strain rate ($\varepsilon_{lc}$) of ECC is lower than that of NC after the axial strain ($\varepsilon_{co}$), which corresponded to the normalized axial strain ($\varepsilon_{cc}$) of 1.0. According to the Mohr-Coulomb theory (as shown in Fig. 11), when the axial stress increases rapidly, the shear failure of cement-based materials will not occur easily if the lateral stress increases rapidly. As far as NC is concerned, cracking caused rapid lateral expansion, which activates a sufficient lateral confinement pressure from the FRP jacket. Therefore, the maximum shear stress will not reach the shear strength of NC. However, the lateral expansion of the ECC developed slowly, which leaded to an insufficient lateral confinement pressure. As a result, ECC is more likely to reach its shear strength than NC, resulting in a drop of axial stress near the yield point in ECC. The reason for the lower lateral strain rate of ECC is related to the "self-confinement" effect of the fibers in ECC. The short fibers in the cement matrix restricted the crack propagation within ECC after reaching the axial strain ($\varepsilon_{co}$) and lead to slow lateral expansion, so that a sufficient lateral confinement pressure from FRP jacket was not activated in time. Because of the relatively large Poisson’s ratio of ECC, the lateral strain rate of ECC in the initial elastic stage is higher. With the formation of cracks, the "self-confinement" effect of ECC gradually dominates, resulting in a lower lateral strain rate comparing with NC. Therefore, a particularly noteworthy result is found that the lateral strain rate of ECC is higher at initial lateral

Table 6

<table>
<thead>
<tr>
<th>Specimens</th>
<th>$f'_{co}$ (MPa)</th>
<th>$\varepsilon_{co}$ (%)</th>
<th>$\varepsilon_{h, rup}$ (%)</th>
<th>$f_{ia}/f'_{co}$</th>
<th>$\rho_k$</th>
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<tbody>
<tr>
<td>E-G2-M</td>
<td>83.3</td>
<td>1.71</td>
<td>1.44</td>
<td>0.137</td>
<td>0.034</td>
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<tr>
<td>E-G5-M</td>
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<td>3.95</td>
<td>1.69</td>
<td>0.403</td>
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<tr>
<td>E-G8-M</td>
<td>217.1</td>
<td>5.61</td>
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<tr>
<td>E-C2-M</td>
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<td>1.26</td>
<td>0.205</td>
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<tr>
<td>E-C5-M</td>
<td>162.8</td>
<td>3.51</td>
<td>1.45</td>
<td>0.590</td>
<td>0.144</td>
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<tr>
<td>E-C8-M</td>
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<td>1.172</td>
<td>0.230</td>
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<td>N-G2-M</td>
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<td>0.96</td>
<td>1.67</td>
<td>0.129</td>
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<tr>
<td>N-G5-M</td>
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<td>3.09</td>
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<td>0.473</td>
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<tr>
<td>N-G8-M</td>
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<td>2.31</td>
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<tr>
<td>N-C2-M</td>
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<td>1.70</td>
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<td>N-C8-M</td>
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<td>4.36</td>
<td>1.60</td>
<td>0.845</td>
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That $f_{ia}$ is the actual maximum confinement pressure and that $\rho_k = 2E_k/\rho_t(f_{ia}/f_{co})/D$ is the confinement stiffness ratio.
Another difference is that for ECC and NC specimens with the same confinement level of FRP, the axial stress enhancement ratio \((\varepsilon_1/\Delta\varepsilon_c)\) of ECC is less than that of NC at the same axial strain in the second ascending branch of the axial stress-strain curves, as shown in Fig. 12. One of the reasons for this difference is also attributed to the lower lateral strain rate \((\varepsilon_{lc}/\varepsilon_c)\) due to the self-confinement effect of fibers within the ECC. To eliminate the influence of compressive strength \((f'_{bb})\), the stress-strain curves of two normal concrete specimens (e.g., HF70-C3 and HF70-C12) from literature [32] with similar compressive strength \((f',c)\) and confinement stiffness \((2E_{frp}/D)\) to that of the ECC specimens (e.g., E-C2-M and E-C8-M) are also plotted in Fig. 12c. The results indicated that the stress enhancement ratio \((\varepsilon_1/\Delta\varepsilon_c)\) of ECC is lower than that of NC.

In addition, the lateral-to-axial strain relationship from Fig. 12 indicate that for the same cement-based material, the lateral strain rates \((\varepsilon_{lc}/\varepsilon_c)\) of both ECC and NC decrease gradually with increasing confinement stiffness \((2E_{frp}/D)\). Hence, the ratio \(\varepsilon_{lc}/\varepsilon_c\) increases with the increment of confinement stiffness. At the ultimate state, there is a linear relationship between the confinement stiffness \((2E_{frp}/D)\) and the ratio of ultimate axial strain to hoop rupture strain \((\varepsilon_{cu}/\varepsilon_{ru})\), as shown in Fig. 13. As mentioned above, the lateral strain rate \((\varepsilon_{lc}/\varepsilon_c)\) of ECC is lower than that of NC, so the ratio \(\varepsilon_{lc}/\varepsilon_{ru}\) of ECC is larger than that of NC.

### 3.4. Lateral strain distribution

The lateral strains of the NC and ECC specimens confined by GFRP jackets with different numbers of FRP layers were plotted as an example in Fig. 14. The standard deviation was used to quantify the uniformity of the lateral strain distribution. Fig. 15 showed the standard deviation of the lateral strain at different average lateral strain \((\varepsilon_{lc,av})\) levels ranging from 0.002 to 0.008. The average lateral strain \((\varepsilon_{lc,av})\) excluded the strain data in the overlap zone measured with L-SG1.

The test results shown in Fig. 15 indicated that, first, for the NC specimens with a given number of FRP layers, little difference was found in terms of the standard deviation of the lateral strain with increasing average lateral strain \((\varepsilon_{lc,av})\). However, for ECC specimens with a given number of FRP layers, there was a significant increase in standard deviation with increasing average lateral strain, which meant that the uniformity of lateral strain tends to deteriorate under such conditions. Second, at the same average lateral strain level, the standard deviation of the lateral strain for the NC and ECC specimens decreased with increases in the number of FRP layers; the decrease was more substantial in the ECC specimens than in the NC specimens. A comparison of NC and ECC specimens with the same number of FRP layers showed that the standard deviation of the lateral strain of the ECC specimens is initially smaller than that of the NC specimens and then gradually exceeded that of the NC specimens as the specimens laterally expand. Third, the average lateral strain level under which the standard deviation of lateral strain in ECC specimens exceeds that of NC specimens increases with increasing number of FRP layers.

The FRP efficiency factor [33] was the ratio of the tested average hoop rupture strain of the FRP in the confined cylinders to the ultimate tensile strain obtained from the FRP flat coupon tests. Fig. 16 showed that the FRP efficiency factors increased with increasing confinement stiffness \((2E_{frp}/D)\). When the confinement stiffness ratio was sufficiently large, the FRP efficiency factors could reach 100%, which meant that the average lateral strain of FRP jacket can even reach the ultimate tensile strain of FRP. The FRP efficiency factor of individual specimens exceeded 100%, which was due to the fact that the ultimate tensile

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**Fig. 9.** Axial stress-strain and lateral-axial strain curves of unconfined NC and ECC.

**Fig. 10.** Normalized lateral strain-axial strain curves.

**Fig. 11.** Mohr-Coulomb theory.
strain of FRP was determined by the average test value. It is not excluded that the ultimate tensile strain of FRP may be larger. In addition, the FRP efficiency factors for most of the confined ECC specimens were lower than those of the confined NC specimens. Therefore, the average value of the FRP efficiency factor from the combination of GFRP and CFRP jackets was 83.9% for the FRP-confined ECC cylinders and 94.8% for the FRP-confined NC cylinders.

Furthermore, Fig. 17 shows the ratio of the average lateral strain to the ultimate tensile strain of FRP for ECC and NC specimens with different confinement stiffness as the axial strain (e.g., $\varepsilon_c = 0.001, 0.005, 0.01, \text{and } 0.02$) increases up to the final failure. It can be seen that for each specimen, the ratio increases with the increase of axial strain. In addition, the Engineering Ultimate State (EUS) [8] determined by the axial strain of 0.01 should be concerned, which has more practical significance for the design of FRP in civil engineering than the failure state.

4. Proposed failure mechanism

Previous studies [34,35] suggested that strain localization caused by splitting cracks in concrete is one of the main reasons leading to lateral strain concentration in FRP. Therefore, based on their own tensile behavior and compressive failure mode of NC and ECC, and the lateral strain distribution of FRP, a failure mechanism of FRP-confined cement-based materials under compression as shown in Fig. 18 was proposed, which can be divided into the following three stages: (I) formation of

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**Fig. 12.** Relationship between stress and strain of the FRP-confined NC and ECC specimens.
microcracks, (II) formation of multiple cracks (for ECC only), and (III) formation and propagation of major cracks.

**Stage I: formation of microcracks**

For both FRP-confined NC and ECC cylinders, before the axial strain reaches the axial strain corresponding to the compressive strength of unconfined cement-based materials ($\varepsilon_{co}$), some microcracks form at internal defect locations in the cement matrix under compression. In this stage, the lateral expansion of cylinders mainly comes from the elastic deformation caused by Poisson’s effect of cement-based materials, and the damage of materials is negligible. Moreover, the lateral tensile strain at this moment is generally less than the first cracking strain ($\varepsilon_{cr}$) of NC or ECC, as shown by point a in Fig. 18a.

**Stage II: formation of multiple cracks**

As the axial compressive stress increases, the principal tensile strain of cement-based materials increases. For the ECC specimens only, after the principal tensile strain of ECC exceeds its cracking strain ($\varepsilon_{cr}$), the bridging fibers within ECC are able to transfer larger tensile stress across the cracks. Thus, multiple fine cracks form until tension softening occurs, which corresponds to the ultimate tensile strain ($\varepsilon_{tu}$) of ECC as shown by point b in Fig. 18a. The lateral expansion in this stage

![Fig. 13. Ratio of ultimate axial strain to the hoop rupture strain.](image)

![Fig. 14. Lateral strain distribution in the FRP.](image)

![Fig. 15. Standard deviations of the lateral strains.](image)

![Fig. 16. Lateral strains at FRP jacket rupture.](image)
is mainly caused by the multiple cracking in ECC. However, the NC does not experience multiple cracking because it does not have strain-hardening behavior in tension.

Stage III: formation and propagation of major cracks

When the principal tensile strain of cement-based material reaches the cracking strain (εcr) of NC or the ultimate tensile strain (εtu) of ECC, major localized cracks form in NC or ECC. Because the cracking strain (εcr) of NC is small, the major cracks form earlier in NC than in ECC, as shown by point a in Fig. 18b. However, the ultimate tensile strain (εtu) of ECC prior to softening is tens to hundreds of times larger than the cracking strain (εcr) of NC. So the formation of major cracks is postponed in ECC, as shown by point b in Fig. 18b. Afterwards, as the axial stress increases, the major cracks continue to develop until compression failure. In this stage, stress redistribution occurs on the FRP jackets at the locations of major crack formation, resulting in a nonuniform distribution of the actual lateral strain (εl,act) in the FRP. When maximum lateral strain in the FRP jackets reaches the ultimate tensile strain (εfrp) of FRP, the FRP jackets rupture as indicated by point c shown in Fig. 18b. Fig. 18c shows the crack development of the cement-based materials and the lateral strain distribution of FRP at compressive failure. The characteristic of the multiple cracks on ECC is indicated on the plan diagram. The bridging fibers between the fine cracks keep the transmission of tensile stress, but do not lead to the fracture of cement matrix until the formation of major cracks. Therefore, the major crack spacing of ECC is larger than that of NC on the plan diagram, but that of NC is smaller due to the loss of tensile stress after first cracking. Moreover, the breaking degree of NC is more serious than that of ECC on the elevation diagram.

According to this proposed failure mechanism, the results shown in Fig. 15 can be well explained. First, for the ECC specimens with a given...
number of FRP layers, when the average lateral strain of FRP was small (e.g., $\varepsilon_{h,ave} = 0.2\%$), ECC was in the stage of multiple cracking. The lateral strain distribution of the ECC specimens at this moment was more uniform than that of the NC specimens, i.e., the standard deviation of lateral strain in ECC was smaller than that of NC. As the lateral expansion increase gradually, the propagation of major cracks reduced the uniformity of the lateral strain, especially for the specimens with lower FRP confinement stiffness. It was even clear that the concentration location of the lateral strain changed in E-G2-M as shown in Fig. 14d. However, when the average lateral strain of FRP further increased, the lateral strain distribution of the NC specimens was apparently more uniform than that of the ECC specimens. This was because with the development of lateral expansion, the major cracks in NC formed earlier and more. Thus, the actual lateral strain in the FRP was close to the larger strain at the location of the major cracks, so that the distribution of lateral strain was more uniform. Whereas for the ECC specimens, the number of major cracks was limited due to the reinforcement of the bridging fibers within ECC. Therefore, the lateral expansion of ECC with relatively few major cracks became even less uniform than that of NC at later stage of loading.

Besides, increasing confinement stiffness of FRP jackets could improve the strain localization of FRP due to stress concentration caused by splitting crack in cement matrix. Therefore, as the number of FRP layers increased, there was a common reduction in the standard deviation of the lateral strain of FRP in both NC and ECC specimens, as shown in Fig. 15.

Again, increasing the confinement stiffness of FRP jackets could enhance the compression hardening behavior of FRP-confined ECC cylinder, which probably reduced the negative effect of compressive damage on ECC at yield point of the axial stress-strain curve, so that the degradation of strain hardening behavior of ECC was delayed. As a result, as the number of FRP layers increases, the average lateral strain level under which the standard deviation of lateral strain in ECC exceeds that of NC was increased. This inference is based on the conclusion given in Kesner et al.’s [36] study, which stated that the early degradation of the tensile strain hardening behavior of ECC was due to lateral expansion cracks caused by compression softening.

At failure, since the lateral strain in FRP was not uniform and the highest strain cannot always be captured with the limited number of lateral strain gauges, the measured hoop rupture strain ($\varepsilon_{h,up}$) was lower than the ultimate tensile strain of the FRP ($\varepsilon_{u,up}$). Moreover, as the number of major cracks in the cement matrix increased, the actual lateral strain distribution of the FRP will become more uniform, and the actual lateral strain was closer to the ultimate tensile strain of the FRP with a high probability. Generally, NC easily formed more major cracks in cylinder due to the strain softening behavior in tension, whereas ECC tended to form fewer major cracks due to the strain hardening behavior in tension. So, the measured hoop rupture strain and the FRP efficiency factor for ECC specimens were lower than those of the NC specimens (see Fig. 16). With increasing confinement stiffness, the FRP efficiency factor increased and finally reached 100%. The results of FRP efficiency factors are basically consistent with the failure modes of the two cement-based materials shown in Fig. 7.

Consequently, based on the above analysis, the significant factors influencing the failure mechanism of FRP-confined cement-based materials under compression were considered to be both the types of cement-based materials and the confinement stiffness of FRP.

5. Prediction of ultimate condition

The axial compression failure of FRP-confined cement-based cylinders is dominated by hoop rupture of the FRP jackets. Therefore, the ultimate compressive strength and ultimate axial strain of FRP-wrapped cylinders at failure should be related to the confinement condition of the FRP jackets. Based on the assessment of 56 existing models for FRP-confined concrete, Ozbakkaloglu et al. [12] suggested that the Lam and Teng’s model [33] and Teng’s model [31] are the most accurate in predicting the strength and strain enhancement ratio of FRP-confined concrete, respectively.

Considering the above reasons, this paper suggests that the equation for the ultimate strength enhancement ratio takes the following form:

$$f'_{cu}/f'_{co} = 1 + k_1f_{h,up}/f'_c = 1 + k_2\varepsilon_c\varepsilon_{h,ave}$$

(1)

where $\varepsilon_c = \varepsilon_{c,upp}/\varepsilon_{h,ave}$ is the strain ratio and $k_1$ is the confinement effectiveness coefficient. In Lam and Teng’s model, $k_1$ is taken as 3.3 for NC.

Fig. 19 shows the ultimate strength enhancement ratio of NC and ECC tested in this study. The ultimate strength enhancement ratio increases approximately linearly with increasing the actual confinement ratio ($f_{h,up}/f'_c$) of the FRP-confined specimens. The test results of the FRP-confined NC cylinders fit well with the model from the Lam and Teng [33]. However, the existing model overestimates the strength enhancement ratios of the FRP-confined ECC cylinders. Therefore, for the FRP-confined ECC specimens, the $k_1$ coefficient can be changed to better reflect the experimental data, thus, the equation proposed in this research is as follows:

$$f'_{cu}/f'_{co} = 1 + 2.5f_{h,up}/f'_c = 1 + 2.5\varepsilon_c\varepsilon_{h,ave}$$

(2)

The reason that the confinement effectiveness coefficient ($k_2$) of ECC is smaller than that of NC is believed to be related to the difference between the peak axial stresses of NC and ECC under triaxial compression. Previous studies have found that the confinement effectiveness coefficient ($k_2$) of ECC determined by the peak stress and confining pressure in the triaxial compression test is 2.866 [10]. This value is less than $k_2 = 3.5$ of NC [37]. This finding indicates that the axial stress enhancement ratio of ECC under constant confining pressure is lower than that of NC. This discrepancy is related to the compression properties of the two types of cement-based materials. This paper does not discuss this phenomenon in detail here, and additional experimental research is needed to further clarify these findings. On the other hand, it is known that the passive lateral confining pressure depends on the confinement stiffness and the lateral strain of the FRP jacket. With the same lateral confinement pressure, since the lateral confinement pressure produced by the lateral strain in FRP jackets is not uniform than that under constant lateral confining pressure, the ultimate compressive strength under confinement of FRP is always less than or equal to the peak stress under triaxial compression. As a result, the confinement effectiveness coefficient under passive confinement ($k_2 = 2.5$) is less than that under active confinement ($k_2 = 2.866$).

In addition, as shown in Fig. 20a, Teng’s model [31] slightly overestimated the strain enhancement ratio. This overestimation is mainly
due to the higher compressive strength of unconfined concrete in this study than that of their study. According to a past study [38], the axial strain enhancement ratio of FRP-confined concrete decreases with increasing compressive strength. Thus, a linear model for predicting the ultimate compressive strain of NC and ECC can be obtained based on the current research data shown in Fig. 13. For the different types of cement-based materials, by substituting the confinement stiffness \((2E_{np}/D)\) with the confinement stiffness ratio \((\rho_{k})\), the fitted equations can be written as follows:

\[
\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1.75 + 6.5\rho_{k}^a \rho_{c}^b
\]

(3a)

\[
\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 19.47\rho_{k}^c + 0.17
\]

(3b)

Eqs. (3) can be further derived into the following form:

\[
\frac{\varepsilon_{cu}}{\varepsilon_{co}} = a\rho_{k}^c + b\rho_{c}^d
\]

(4)

where \(a\) and \(b\) are the fitted constants.

To apply to the ultimate compressive strain of unconfined cement-based materials, the equation of the strain enhancement ratio is fitted in the same form as Eq. (4). Given the limitations in the present test data, it is assumed that the ratio of the ultimate axial strain to the strain at peak stress is 1.75 [31] for both unconfined NC and ECC. Thus, the design equations of the strain enhancement ratio for NC and ECC are proposed as Eqs. (5a) and (5b), respectively. Fig. 20b shows that Eqs. (5a) and (5b) provide close predictions of the strain enhancement ratio, for which the coefficients of determination \((R^2)\) of ECC and NC are 0.935 and 0.965, respectively.

For ECC specimens, \(\varepsilon_{cu}/\varepsilon_{co} = 1.75 + 0.30\rho_{k}^c + 13.94\rho_{k}^d\rho_{c}^e\)

(5a)

For NC specimens, \(\varepsilon_{cu}/\varepsilon_{co} = 1.75 + 18.84\rho_{k}^d\rho_{c}^e\)

(5b)

6. Conclusions

In this research, axial compression tests were conducted on FRP-confined ECC cylinders. The following conclusions can be drawn from this study:

1. Similar to FRP-confined NC specimens, ECC cylinders confined by FRP jackets exhibit compression hardening behavior with a second ascending branch in the axial stress-strain curve.

2. The self-confinement effect of ECC is considered to be the most critical mechanism affecting the axial compressive behavior and the failure mode of specimens. The self-confinement effect can restrain the lateral expansion of ECC and reduces its lateral strain rate, which results in the formation of inclined cracks on unconfined ECC, and the large drop of axial stress near the yield point of the axial stress-strain curve and the change of the ultimate compressive strength and strain of FRP-confined ECC.

3. According to the lateral strain distribution in FRP, the compressive failure mechanism of FRP-confined NC and ECC is proposed including three distinct stages: formation of microcracks, formation of multiple cracks (for ECC only), and formation & propagation of major cracks. The proposed mechanism accounts for the effects of different tensile behaviors between NC and ECC, and the confinement stiffness of FRP on the failure modes and FRP efficiency factor.

4. Based on the testing data, a new set of equations is proposed for predicting the ultimate compressive strength and axial strain of FRP-confined ECC cylinders. Both the confinement stiffness ratio and strain ratio are taken as the main parameters in the proposed equations.

This paper mainly focuses on the compressive behavior and failure mechanism of FRP-confined ECC cylinder under monotonic compressive loading. The properties of FRP-confined ECC cylinder under cyclic compressive loading, such as stiffness degradation and damage evolution [39,40], will be further studied in the future.

CRediT authorship contribution statement

Zheng Dang: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. Peng Feng: Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration. Jia-Qi Yang: Writing - original draft, Software, Data curation, Visualization. Qian Zhang: Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compstruct.2020.112191.

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