低干缩延性材料-混凝土复合梁抗弯性能:模拟与验证

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摘要：基于断裂力学建立了低干缩延性纤维增强水泥基材料(LSECC)-混凝土复合梁的抗弯模型, 模拟了不同强度组合、不同LSECC层厚的复合梁抗弯性能。结果表明：在梁底复合低干缩延性材料不仅可提高梁的抗弯承载力, 而且大幅提升梁的延性; 复合梁的承载力和延性提升与材料强度和LSECC层厚相关; 当LSECC强度较上层混凝土强度高时, 复合梁的抗弯承载力和延性受LSECC层厚影响显著, 随层厚的增加而提高。对不同强度组合、不同LSECC层厚的复合梁实施了三点弯曲试验, 模拟结果与试验结果吻合良好。

关键词: 低干缩延性纤维增强水泥基材料; 混凝土; 复合梁; 抗弯性能

1 引言


LSECC是正常采用的, 尤其是在结构中, 其优势可以得到最充分的利用。[1-2] 基于经济考虑, 建议局部采用LSECC作为结构中受弯部分的材料。[3-4] 多条细微裂纹在表面形成, 可以有效地进行结构的变形, 并且对结构的耐久性影响较小。[5]
age characteristic of LSECC makes the deformation of LSECC compatible with concrete.

This paper was to focus on the flexural performance of LSECC-concrete composite beam in which a layer of LSECC is applied beneath a layer of concrete. The crack propagation in the composite beam was simulated based on the fracture mechanics criteria. In addition, the effect of the strength of LSECC and concrete as well as the thickness of LSECC layer on the overall bending behavior of the composite beam was investigated. The prediction by a model was validated in terms of bending load capacity as compared to the experimental results of composite beams under a three-point bending load.

1 Flexural model of LSECC-concrete composite beam

In the model, the fine and coarse aggregates in mortar or concrete are viewed as bridging elements, so that the cement paste serves as a fully brittle matrix. The fracture toughness acts as a governing parameter for crack propagation. In other words, crack propagates when

\[ K_{\text{tip}} = K_{IC} \]

where \( K_{IC} \) is the fracture toughness of matrix and \( K_{\text{tip}} \) is the crack tip stress intensity factor resulting from both the applied load and the bridging stresses.

Figure 1 shows a cracked LSECC-concrete composite beam with bridged crack length \( a \), external bending load \( M_a \), and bridging stresses along crack plane \( \sigma_b(x) \). In Fig. 1, the crack tip stress intensity factor can be obtained by summing the contribution \( K_a \) of external load and \( K_b \) of the bridging stress, i.e.,

\[ K_{\text{tip}} = K_a + K_b \]

The contribution \( K_a \) can be calculated through the stress field \( \sigma_a(x) \) that would exit on the crack plane in the absence of the crack under specific remote loading. For a LSECC-concrete composite beam, the stress field resulted from bending load can be expressed as

\[ \sigma_a(x) = \frac{M_a}{\alpha E I} \frac{1}{x} \quad x < h_{\text{ECC}} \]

\[ \sigma_a(x) = \frac{M_a}{I} \frac{1}{x} \quad x \geq h_{\text{ECC}} \]

where \( \alpha \) is the ratio of the Elastic modulus of concrete to LSECC. \( I \) is the inertia moment of the LSECC-concrete composite beam, in which the calculation should take the cross section conversion into account. \( h_{\text{ECC}} \) is the thickness of LSECC layer. For a beam under three-point bending, \( M_a = PL/4 \), where \( P \) is the load at mid-span and \( L \) is the span length between two supports. Then, \( K_a \) is calculated by

\[ K_a = 2 \int_0^a G(x,a,h) \sigma_a(x) dx \]

where \( G(x,a,h) \) is the weight function that represents the contribution of a unit force on the crack surface to the crack tip stress intensity factor.\(^7\) For a beam under bending, it is given by

\[ G(x,a,h) = \frac{h_i(x/a,a/h)}{\sqrt{\pi}a(1-x^2/a^2)^{3/2}} \]
Marshall, [8] we consider that the crack opening profile \( w(x) \) is related to the stress field \( \sigma \) along crack plane resulting from external load and bridging stress \( \sigma_b \) as

\[
\frac{8}{E} \int_0^a G(x, \alpha', h) [\sigma_b(x') - \sigma_b(x)] \, dx' \int_0^a \frac{\alpha' \cdot h}{2} \, d\alpha' .
\]

(8)

For a given crack length \( a \) and stress-crack width relationship, the critical external load \( M \) in terms of bending load \( P \) and crack profile \( w(x) \) can be thus obtained by solving Eqs. 1, 2 and 8. The crack mouth opening displacement (CMOD) can be calculated from Eq. 8 as well. The calculated results can be presented as the load-crack mouth opening displacement (CMOD) curve.

2 Material parameters for model input

In this paper, the fracture toughness was calculated by the critical load at which crack starts to propagate, i.e., the starting point of nonlinearity in the load-CMOD curve resulting from three-point bending test on notched beams. [9] Two plain concretes (i.e., C30 and C80) and two LSECCs (i.e., LSECC0.55 and LSECC0.35) were combined to form four kinds of composite beams, respectively. Table 1 shows the corresponding values of \( K_{IC} \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C30</th>
<th>C80</th>
<th>LSECC0.55</th>
<th>LSECC0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{IC} )/(MPa ( \cdot ) m(^{1/2}))</td>
<td>0.12</td>
<td>0.29</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>( a_0 )/mm</td>
<td>1.00</td>
<td>0.75</td>
<td>1.00</td>
<td>0.75</td>
</tr>
</tbody>
</table>

An inverse analysis based procedure developed by Zhang et al. [10-11] was used to determine the stress-crack width relationship. For the numerical calculation, a multiple linear function was used to simulate the stress-crack width relationship, i.e.,

\[
\sigma_b = k_i w + \sigma_{0i} , \quad w_{i-1} < w < w_i (i = 1, 2, 3, ...) .
\]

(9)

where \( k_i \) is the slope for \( w \in [w_{i-1}, w_i] \), \( \sigma_{0i} \) is the cracking strength of the matrix. The slope of each linear portion of the stress-crack width relation, \( k_i \), is determined based on the fitting of calculation results to the test results of three-point bending tests. More details of the parameter extraction procedures can be found in the reference. [10]

Figure 2 shows the derived stress-crack width relationship of each concrete and LSECC.

In cement matrix, flaws are typically the sources where crack initiates. In the model, the initial flaw is an equivalent crack resulted from defects on the surface of the beam. According to the fracture toughness \( K_{IC} \) determined from pre-notched beam, the initial unbridged flaw size \( a_0 \) is back-calculated, and Table 1 shows the results.

3 Results and experimental validation

In the model, the LSECC layer was selected as 0, 30, 50, 70 and 100 mm, respectively. The beam height of 100 mm and span of 350 mm were assumed. Four types of LSECC-concrete composite beams were selected, which were labeled as LSECC0.55/C30, LSECC0.55/C80, LSECC0.35/C30 and LSECC0.35/C80, respectively. According to the thicknesses of LSECC layer and concrete layer in each type of beam, the specimens were labeled as ecc0.pc100, ecc30.pc70, ecc50.pc50, ecc70.pc30 and ecc100.pc0, respectively. Figure 3 shows the predicted results in terms of bending load versus crack mouth opening displacement (CMOD).

It is seen that the flexural behaviors of LSECC-concrete composite beams are very different from plain concrete beams. On the bending load-CMOD curve of each plain concrete beam, there is a rapid drop following the peak point, which exhibits the brittleness of plain concrete. When the LSECC layer is applied at the bottom of the beam, the flexural performance of the beam changes from bending strain softening to strain hardening. In addition, the flexural performance of composite beams...
is significantly affected by the strength matching of ductile LSECC material and plain concrete. As a low strength LSECC (0.55) is combined with a low strength concrete (C30), the ductility and load capacity of composite beams both can be increased at above a certain value of LSECC thickness. However, the load capacity is decreased when a low strength LSECC (0.55) is combined with a high strength concrete (C80). As a high strength LSECC (0.35) is combined, the ductility and load capacity of composite beams are always improved simultaneously when LSECC layer is thick enough.

To verify the predictions by the model, three-point bending tests were carried out on LSECC-concrete composite beams. Four types of LSECC-concrete composite beams were selected, which were labeled as LSECC0.55/C30, LSECC0.55/C80, LSECC0.35/C30 and LSECC0.35/C80, respectively. Tables 2 and 3 show the mix proportions of the two concretes and two LSECCs, which were the same as used in the notched beams for solving the stress-crack opening relationship. The cement type was P·O 42.5. The fiber used was polyvinyl alcohol fiber (PVA).

Table 4 shows the fiber properties. In each batch, two specimens with dimensions 100 mm×100 mm×400 mm were cast. Three different LSECC layer thicknesses of 30, 50 and 70 mm were used in the composite beams. During the preparation of the beams, the LSECC layer was cast first. After casting the LSECC layer for 2 h, the concrete layer was cast. Also, the plain concrete and whole LSECC beams were also cast as references. The displacement control at a rate of 0.10 mm/min was used in the three-point bending test. It is difficult to measure the CMOD since the cracks under the beam are randomly distributed. Thus, the mid-point deflection was measured instead. The load was recorded during test as well.

Table 2  Mix proportions and compressive strength of concretes

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Mass ratio</th>
<th>Compressive strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
<td>Water</td>
</tr>
<tr>
<td>C30</td>
<td>1.0</td>
<td>0.62</td>
</tr>
<tr>
<td>C80</td>
<td>1.0</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Table 3  Mix proportions and compressive strength of LSECCs

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Mass ratio</th>
<th>Volume fraction of fiber/%</th>
<th>Compressive strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Composite cement</td>
<td>Water</td>
<td>Sand</td>
</tr>
<tr>
<td>LSECC0.55</td>
<td>1.000</td>
<td>0.550</td>
<td>0.800</td>
</tr>
<tr>
<td>LSECC0.35</td>
<td>1.000</td>
<td>0.350</td>
<td>0.300</td>
</tr>
</tbody>
</table>

Table 4  Properties of PVA fiber

<table>
<thead>
<tr>
<th>Density/(g cm⁻³)</th>
<th>Tensile strength/MPa</th>
<th>Elastic modulus/GPa</th>
<th>Diameter/mm</th>
<th>Length/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>1620</td>
<td>42.8</td>
<td>0.039</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 4 shows the typical bending test results in terms of load-deflection diagrams for different kinds of beams. From these results, plain concrete beams exhibit a brittle property under a bending load. With the addition of LSECC layer, the improvement on bending load capacity depends on the combinations between concrete and LSECC. As a high strength LSECC (0.35) is employed, the ductility and load capacity of composite beams are always improved simultaneously when LSECC layer is thick enough. The experimental results are similar to the predicted data. A particular emphasis is put on the comparison of load capacity. Figure 5 shows the comparison between the predicted flexural load capacity and the experimental results from three-point bending tests. Clearly, the predicted data agree well with the experimental results.
4 Conclusions

A fracture mechanics based model for the simulation of the flexure performance of LSECC-concrete composite beams was proposed. In the model, the contribution of external applied load and bridging stress to crack tip stress intensity factor were considered separately. The crack propagated when stress intensity factor achieved the fracture toughness of the matrix.

The complete flexural behavior of the composite beam in terms of load-CMOD curves was predicted by this model. With the addition of LSECC layer, the improvement on the bending load capacity depended on the combination between concrete and LSECC. As a high strength LSECC was used, the ductility and load capacity of composite beams were improved simultaneously. The flexural performance of LSECC-concrete beams was also investigated experimentally by three-point bending tests. The experimental results were compared with the predicted data in terms of load capacity improvement. The experimental results were in reasonable agreement with the predicted data. The model could be used in the optimization of the composite structures.

References: