Simulation and Experimental Study on Fracture Properties of Lightweight Aggregate Foam Concrete

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Abstract. Lightweight aggregate foam concrete (LAFC) is a quasi-brittle porous composite material with a large number of holes and micro-cracks in the internal structure, which directly affect the durability and reliability of the building structure. In this study, the extended finite element method (XFEM) is used to build a fracture performance simulation model of three-point bending (3-p-b) for the LAFC. The crack propagation pattern and the loading force variation law are investigated and compared with the fracture test. The results show that the calculated results are in good agreement with the experimental results, which indicate that the XFEM is an effective method to study the fracture properties of the LAFC.

1. Introduction
Lightweight foamed concrete (LAFC) is widely used in various construction projects due to its lightweight, heat insulation, sound insulation, energy saving, fire resistance and seismic performance. It has become one of the new building materials with the rapid development in architectural material industry [1,2]. However, due to various defects (bubbles, micro-cracks and impurities) in the LAFC, under the action of external force, the micro-crack will form macro-cracks, which will eventually lead to a structural damage. To improve the mechanical properties of LAFC, a lot of theoretical research and experimental research have been carried out. Previous studies mainly use the macroscopic model method [3], which regard the concrete structure as a homogeneous isotropic material. However, it cannot reveal the process of crack generating, expanding and destroying inside the concrete structure. With the rapid development of computer technology, meso-mechanical analysis methods have been applied to the study of mechanical properties of LAFC. Many micro-mechanical analysis models have emerged, such as stochastic particle models [4], stochastic mechanical properties models [5], the rigid body spring element model [6,7], aggregate structure model [8], etc.. The mechanical properties of LAFC were investigated from different angles.

In order to overcome the difficulties caused by the traditional finite element in the calculation of intermittent problems such as cracks, holes, inclusions, etc., in which the high-density meshing is required, the Beleytachko research team of Northwestern University in USA proposed the extended finite element method (XFEM) in 1999[9, 10]. The XFEM uses a shape function with discontinuous properties to represent the discontinuity in the calculation region, so that the description of the discontinuous field is completely independent of the mesh boundary, which can well simulate the crack path and the heterogeneous material with holes and inclusions, so that the crack growth
simulation also does not need to re-mesh the mesh. It is an effective numerical method for solving discontinuities such as cracks, holes, and inclusions [11, 12].

In this paper, the ceramsite foam concrete is taken as an example, the crack propagation law of LAFC is studied by using the XFEM. The numerical calculation results were verified by physical test.

2. Numerical simulation method of fracture performance

2.1 Random generation method of light aggregates and pores

The sample is simulated by two-dimensional plane simulation in the paper. The size of the model is 150 (mm)× 40 (mm), which refers to the physical 3-p-b test sample size. When defining the material properties, the given thickness is 35 mm. The three aggregates (coarse, medium and fine) and pores are contained in the model. The specific parameter assignment of each group is shown in Table 1.

| species          | Number | Radius (mm) | Area fraction (%) |
|------------------|--------|-------------|-------------------|
| Coarse aggregate| 3      | 10          | 35                |
| medium aggregate | 6      | 7.25        |                   |
| fine aggregate   | 12     | 5           |                   |
| pore             | 97     | 0.5         | 1                 |

The complexity of LAFC modeling depends primarily on the modeling of aggregates and pores. Since there are three radius of aggregates, the steps of modeling the aggregate are described below. The steps of modeling the pores can be referred to the following steps, and are not described herein again.

Step 1: Determine the number of aggregates

In this model, the ratio of coarse, medium and fine aggregate is 1:2:4, based on which the area of a group of aggregates is calculated.

\[
S = \pi \times (1 \times r_1^2 + 2 \times r_2^2 + 4 \times r_3^2)
\]

(1)

Where, \(r_1, r_2\), and \(r_3\) are the radius of the aggregate, respectively. Take \(a\) and \(b\) for the model length and width, then the area \(n_0\) through a group of aggregates is as follows

\[
n_0 = \frac{a \times b \times p}{S}
\]

(2)

Where, \(p\) is the area ratio of the aggregate (\(p=35\%\)). Take \(n_0\) as an integer

\[
n_1 = \text{Floor}(n_0)
\]

(3)

Where, floor is the rounding function. If \(n_0-n_1 \geq 0.5\), take \(n_2=n_1+1\), if \(n_0-n_1 < 0.5\), take \(n_2=n_1\). \(n_2\) is the number of groups of the final determined aggregate.

Step 2: Randomly generate the center coordinates of the temporary aggregate

The aggregates are randomly placed in a specific two-dimensional range. The formation of aggregates satisfies the Monte Carlo random number method, in which the aggregate center range setting is as follows:

\[
\begin{cases}
(r+t) \leq x \leq (a-r-t) \\
(r+t) \leq y \leq (b-r-t)
\end{cases}
\]

(4)

where, \(t\) is the transition zone thickness between the aggregate and the mortar.

Step 3: Judgment of aggregate boundary conditions

The judgment expression of the boundary condition is
where, $d$ is the distance between any two aggregates and the condition for satisfying the non-interference of any two aggregates is $d > (r_i + r_k + 2t)$, $r_i$ is the radius of the aggregate at the center $(x_i, y_i)$ of the circle, $r_k$ is the radius of the aggregate at the center $(x_k, y_k)$ of the circle. Therefore, for the aggregate $i$ is generated, it is necessary to judge the boundary conditions of the aggregates of $i$-1 times. As long as the judgment requirements of the boundary conditions are not met, the result of $(x_i, y_i)$ is rejected and a new $(x_i, y_i)$ is regenerated. The $(x_i, y_i)$ and $r_i$ that satisfy the judgment requirements of the boundary conditions are stored in the custom file list.

Step 4: Establishment of aggregates and corresponding transition zones

By setting the center coordinates of the aggregate and the pores obtained in the above steps, Using the list file, the aggregate, transition zone and pores are sequentially established by the Python language control software.

The LAFC simulation model established by the above method is shown in Figure 1.

![Figure 1 The LAFC simulation model](image)

### 2.2 Finite element simulation of a 3-p-b experimental model with notch

The LAFC can be seen as a four-phase composite material composed of light aggregate, cement mortar, pores and the interface between aggregate and mortar. The XFEM method was used to calculate the crack propagation process of the LAFC specimens, and the fracture mechanism of the specimen was visually reflected.

(1) Material property processing

The simulation model in this paper is consistent with the experimental model. Therefore, the calculation model involves the LAFC beam, the upper and lower chucks, and the initial pre-cracking. Among them, the upper and lower chucks and the initial pre-crack do not need to be given material properties. The parameters of the aggregate, mortar and interface transition zone (ITZ) in the LAFC simulation beam are shown in Table 2.

| Component   | Modulus of Elasticity E (GPa) | Poisson's Ratio | Strength f_t (MPa) |
|-------------|-------------------------------|----------------|--------------------|
| Aggregate   | 8000                          | 0.2            | 0.2                |
| Mortar      | 12000                         | 0.2            | 0.6                |
| ITZ         | 10000                         | 0.2            | 0.48               |

(2) Treatment of boundary and contact conditions

It's needed to couple the chuck acting point to the selected reference point on the specimen. For the two chucks on the bottom surface, the degree of freedom of one of the action points is set to $(U_1=0, U_2=1, UR_3=0)$. Here, $U_1$—x direction freedom, $U_2$—y direction freedom, $UR_3$—rotational freedom, 0-free, 1-constraint), and the degree of freedom of the other acting point is set to $(U_1=1, U_2=1, UR_3=0)$. The degree of freedom of the action point of the upper chuck is set to $(U_1=0, U_2=1, UR_3=0)$. Considering the problem of computational convergence, the smooth step is selected on the loading mode in the Y direction. In terms of contact, the tangential friction coefficient between the chuck and the concrete is 0.2, and the normal direction is Hard Contact.

(3) meshing
In order to avoid the non-convergence of the crack caused by the crack in the irregular mesh distribution, the Medial Axis algorithm is selected as the mesh segmentation algorithm of the crack extension region, and the rest is selected by the Advancing Front Mesh Segmentation algorithm. Due to the presence of pre-cracks, the crack propagation area is reduced to a local area to reduce the amount of calculation. The effective extension area of the XFEM is set to the middle area. The mesh of the crack propagation region is refined, in which the mesh size is taken as 0.25 mm. The mesh of the local region in contact with the chuck is refined to 0.1 mm, and the remaining mesh size is taken as 0.75 mm. The total number of the elements in the model is 102,727. The finite element calculation model is shown in Figure 2.

Figure. 2  Finite element calculation model

2.3 Extended finite element method
The extended finite element method (XFEM) is based on the ordinary finite element method. To effectively solve the discontinuity problem, a node extension function is designed in the XFEM. It includes two functions: the progressive function near the crack tip indicates the stress singularity near the crack tip, the discontinuous function indicates the displacement jump at the crack face. The overall displacement function can be expressed as [13]

\[
\begin{align*}
\mathbf{u}^h(x) = \sum_{i \in N} N_i(x) \begin{bmatrix}
\mathbf{u}_i + H(x) \mathbf{a}_i + \sum_{a=1}^{4} F_a(x) \mathbf{b}_a^n \\
\end{bmatrix}
\end{align*}
\]

(6)

In the formula:
- \(N_i(x)\)-common node displacement function;
- \(\mathbf{u}_i\)-the node freedom degrees of regular shape function (applicable to all nodes in the model);
- \(H(x)\)- discontinuous step function along the crack surface;
- \(F_a(x)\)-the progressive function of the crack tip.

\[
H(x) = \begin{cases} 
1 & \text{if } (x - x^*)n \geq 0 \\
-1 & \text{otherwise}
\end{cases}
\]

(7)

Where, \(x\) is the sample point, \(x^*\) is the nearest point to \(x\); \(n\) is the unit normal vector.
- \(\mathbf{a}_i\)- the freedom degree vector of extended node (only valid for element nodes whose shape function is cracked);
- \(\mathbf{b}_a^n\)- the freedom degree vector of extended node (only valid for element nodes whose shape function is cut by the crack tip);
- \(F_a(x)\)- the progressive function of the crack tip.

For the isotropic materials, \(F_a(x)\) expression is [14]:
\[
[F_ \alpha (x), \alpha = 1 \rightarrow 4] = \left[ \sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2}, \sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \sin \frac{\theta}{2} \right] \tag{8}
\]

where, \((r, \theta)\) denotes the polar coordinates in the local crack field coordinate system. The progressive function of the crack tip is not limited to the modeling of cracks in isotropic elastic materials.

The XFEM is based on the theory of standard finite element, retains the advantages of traditional finite element, alleviates the shortcomings caused by meshing of crack surface, avoids the re-division of mesh. When performing crack propagation calculations, it is significantly better than the standard finite element method. Currently, commercial software such as Abaqus has added an analysis module of XFEM.

3. Analysis of numerical calculation results

The crack propagation process of the pre-cracked concrete beam under force is shown in Figure. 3. It can be seen that, for lightweight aggregate concrete, when the crack encounters the aggregate, the crack propagates straight through the aggregate.

The loading force-displacement curve is shown in Figure. 4. It can be found that, when the load reaches the maximum value, the load decreases rapidly, indicating that the LAFC is brittle damage.
4. Experimental verification

To verify the correctness of the numerical calculation results, the 3-p-b fracture performance test of the LAFC was carried out. The material used is a kind of ceramsite foam concrete material. The main distribution ratio of the material is shown in Table 3.

Table 3 Ceramsite foam concrete material mix ratio

| Material        | Distribution | Foam /m³ |
|-----------------|--------------|----------|
| Cement / Kg     | 300          |          |
| Ceramsite /Kg   | 400          |          |
| Fly ash /Kg     | 100          |          |
| Foam /m³        | 0.22         |          |

The sample size is 150mm × 40mm × 35mm (length × height × thickness). The pre-crack 3-p-t test was completed on a CMT5105 universal testing machine (see Figure 5). The fracture condition of some samples is shown in Figure 6. Comparing with Figure 3, the crack propagation law is consistent, which indicates that the failure form of lightweight aggregate concrete is different from ordinary concrete.

The loading-displacement curves of three samples are shown in Figure 7 and the test results of the whole sample are shown in Table 4. Compared with the simulation results (Figure 4), the variation law of the loading force-displacement curve is consistent. Due to the seriously non-uniformity of the LAFC, the test data has a certain discrete, the maximum load is between 131.2~214.6N, and the average value is 168N. The simulation result (185N) is within this range and the relative error from the experimental mean is 10%. It is indicated that the numerical method can be used to study the fracture properties of the LAFC.
| No. | Pmax (N)  | ΔL (mm) | No. | Pmax (N)  | ΔL (mm) |
|-----|-----------|---------|-----|-----------|---------|
| 1   | 159.9     | 0.155   | 12  | 131.2     | 0.174   |
| 2   | 165.7     | 0.255   | 13  | 158.9     | 0.215   |
| 3   | 164.2     | 0.312   | 14  | 152.7     | 0.312   |
| 4   | 146.5     | 0.222   | 15  | 212.3     | 0.156   |
| 5   | 162.5     | 0.109   | 16  | 172.0     | 0.163   |
| 6   | 161.8     | 0.152   | 17  | 158.5     | 0.206   |
| 7   | 275.5     | 0.142   | 18  | 152.5     | 0.126   |
| 8   | 146.8     | 0.212   | 19  | 150.0     | 0.252   |
| 9   | 194.8     | 0.182   | 20  | 140.6     | 0.124   |
| 10  | 176.8     | 0.195   | 21  | 131.2     | 0.139   |
| 11  | 214.6     | 1.179   | Mean| 168.0     | 0.190   |

5. Conclusions

In this study, the XFEM is used to calculate the fracture performance of the LAFC, and this method is verified by experiments. The relative error between the calculation and experimental results is only 10%. It indicates that the XFEM is an effective method to investigate the fracture properties of the LAFC. It avoids re-mesh in crack propagation calculations, and significantly increases the computational speed and accuracy. By using this simulation method, the fracture properties of the LAFC under various material ratios can be studied efficiently, which can be further used to optimize the material fracture properties.

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