Tensile Properties of Concrete with Irregular Aggregate Shapes

Lei Tian*, Yawei Li

Lanzhou Jiaotong University, Lanzhou, Gansu, 730000, China

Corresponding author's e-mail:392768814@qq.com

Abstract. Concrete is an important heterogeneous material used in engineering structures and infrastructure projects. Studying its mechanical properties and failure mechanism from meso-scale could provide supplementary insights for experimental research. In this study, the geometric concrete model of three aggregate types—pebble, gravel, and convex polygon—is established via MATLAB aggregate deformation program. Subsequently, the model is imported into the ABAQUS software to numerically simulate the failure mode and macro-mechanical properties of concrete specimens under uniaxial tensile conditions. The results show that the aggregate shape significantly affects the tensile strength and failure mode of concrete. The tensile strength and elastic modulus of the gravel aggregate concrete specimens were 1.9% and 5.7% higher than those of the convex polygonal aggregate concrete specimens. Moreover, the shape of the aggregate affects the expansion path of the cracks. Utilizing a meso-numerical model with irregular aggregates not only better approximates the actual geometric shape but also produces numerical simulation results that closely align with real-world conditions.

Keywords: Concrete; meso-numerical simulation; irregular aggregate; uniaxial tension

1 INTRODUCTION

Concrete is an important material used in engineering structures and infrastructure construction such as large-scale power stations, dams, bridges,and tunnels. Its mechanical properties serve as an important basis for the seismic design and static and dynamic simulation analysis of concrete structures. However, as a multiphase composite material composed of aggregate, mortar, and the interface transition zone between them, it is difficult to capture the nonlinear mechanical behavior resulting from the randomness and heterogeneity of its meso-component distribution solely through macro-level experimental research and theoretical analysis. Therefore, there is a need to explore the meso-numerical simulation of concrete[1, 2].

The failure of concrete is simulated through the finite element method from meso-scale. At present, the geometric models of random aggregates are generated mainly based on geometric partitioning[3, 4] and grid mapping[5, 6], Although the grid

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mapping-based method has exhibited its superiority in grid quality, the model generated through geometric partitioning is more in line with the actual situation. Among the geometric models generated through geometric partitioning, common aggregate shapes are mostly simplified into circular and elliptic shapes[7-9], to improve the generation efficiency of aggregates and the grid quality of models. On this basis, the aggregate boundary experiences an outward or inward offset to generate an interfacial transition zone. The generation of geometric models according to this method, although efficient, does not reflect the influence of aggregate shape. It has been found[10] that aggregate shape has a more significant effect on the mechanical properties and crack patterns of concrete. Among the meso-numerical concrete models, the common ones include the transition motor method[10], which regards the interfacial transition zone as high-porosity mortar and implements the corresponding equivalent deduction of mechanical parameters; the interfacial spring element method[11, 12], which characterizes the mechanical behavior of the interfacial transition zone by establishing the spring with the multiple node pairs at the same node position from the junction between aggregate and mortar elements; the cohesive element method[13, 14], which finds all element pairs sharing the same two nodes in the interfacial transition zone elements and mortar elements of the model and embeds cohesive elements to simulate concrete fracture.

In this study, the meso-numerical model of concrete with irregular aggregate shapes is established considering the actual aggregate gradation, and the failure modes of concrete specimens in case of uniaxial tension are simulated. Moreover, the effect of the aggregate shape on the tensile properties of concrete is systematically explored, expecting to provide a reference for improving the numerical simulation accuracy of concrete.

2 GEOMETRIC MODELING OF CONCRETE

2.1 Expansion Deformation of Parametric Curves

Under 2D circumstances, the aggregate profile can be regarded as an irregular closed curve obtained through the topological deformation of the ellipse. The expansion factor function[15] controlling the deformation of the parameter curve is defined as follows:

For the intervals $[a_0 - r_1, a_0 + r_1]$ and $[a_0 - r_2, a_0 + r_2]$ symmetrical about a_0 in the 1D real number space $\mathbf{R}^1$, $0 \le r_1 < r_2$, $t = (x - a_0)^2$ is set, and the C^∞ function on $\mathbf{R}^1$ is formulated:

$$g(x, a_0, r_1, r_2) = g(t) = \begin{cases} e^{\frac{1}{(t - r_1^2)(t - r_2^2)}}, & 0 \le r_1^2 < t < r_2^2 \\ 0, & t \le r_1^2, t \ge r_2^2 \end{cases} \tag{1}$$

The followings are set:

$$B(x, a_0, r_1, r_2) = B(t) = \frac{\int_t^{+\infty} g(s)ds}{\int_{-\infty}^{+\infty} g(s)ds} \tag{2}$$

Then, $B(x)$ is referred to as the expansion function on $\mathbf{R}^1$.

Suppose $P(t)=(x(t),y(t))^{\mathrm{T}}$, $t\in[a,b]$ is set as a Class C^r $(r\geq 1)$ curve, the interval is $[a_0-r_1,a_0+r_1]\subseteq[a_0-r_2,a_0+r_2]\subseteq[a,b]$, the center is $O'(a_0)=(x(a_0),y(a_0))^{\mathrm{T}}$, $\alpha_1,\alpha_2\in\mathbf{R}$ is taken, $D=diag(\alpha_1,\alpha_2)$ is set as the expansion coefficient matrix, and then the post-deformation curve $\boldsymbol{P}_{\mathrm{d}}(t)$ presents the following relation with the pre-deformation curve $\boldsymbol{P}(t)$:

$$\boldsymbol{P}_{\mathrm{d}}(t)=(DB(t,a_0,r_1,r_2)^k+E)(\boldsymbol{P}(t)-O')+O',\ t\in[a,b] \tag{3}$$

where E is a unit matrix and $k\in\mathbf{N}$ (natural number set) represents the fullness index. The contraction-expansion direction, amplitude, and fullness of the curve can be adjusted by changing α_1,α_2, and k, and the overall or local deformation can be achieved by changing the interval.

2.2 Generation of Irregular Aggregates

With the generation of pebble aggregate as an example, the center of the ellipse on the plane is set at point $O(x_0,y_0)^{\mathrm{T}}$, and the parameter equation of the ellipse can be expressed as follows:

$$\Gamma:\boldsymbol{P}(t)=\begin{pmatrix}x(t)\\ y(t)\end{pmatrix}=A\begin{pmatrix}a\cos t\\ b\sin t\end{pmatrix}+\begin{pmatrix}x_0\\ y_0\end{pmatrix} \tag{4}$$

Considering that pebbles are formed by the rolling friction caused by water scouring stones in the natural environment, the covering ellipse is controlled to expand inward, and the contraction-expansion coefficient matrix is taken as $D_{\mathrm{i}}=diag(\alpha_{1_{\mathrm{i}}},\alpha_{2_{\mathrm{i}}})$. The contraction-expansion coefficient is randomly obtained using the uniform distribution within $[-0.16,-0.10]$, and the fullness index may be appropriately taken as $k_{\mathrm{i}}=1$, so the contour line of the pebble aggregate is obtained by successive contraction-expansion in each interval as follows:

$$\boldsymbol{P}_{\mathrm{d}}(t)=(x_{\mathrm{d}}(t),y_{\mathrm{d}}(t))^{\mathrm{T}}=\sum_{i=1}^{n}\left\{\left[D_{\mathrm{i}}B(t,a_{0_{\mathrm{i}}},r_{\mathrm{i}})+E\right]\left[\boldsymbol{P}(t)-O\right]+O\right\} \tag{5}$$

where $t\in[0,2\pi]$, and the area enclosed by the contour line expressed by the above equation is:

$$S_{\mathrm{d}}=\frac{1}{2}\int_0^{2\pi}\|P_{\mathrm{d}}(t)-O\|^2\,dt \tag{6}$$

According to the above ideas, by adjusting the relevant parameters of expansion deformation, the MATLAB program was compiled to generate single gravel aggregate, pebble aggregate, and convex polygonal aggregate, as shown in Figure 1.

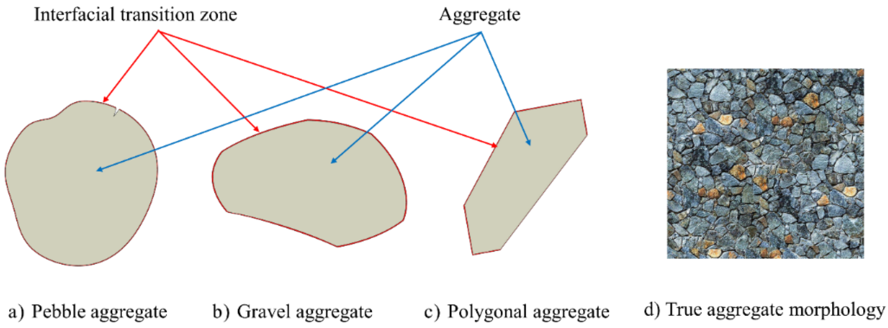


Fig. 1. Single aggregates in three different shapes and true aggregate morphology.

3 PARAMETER SETTINGS

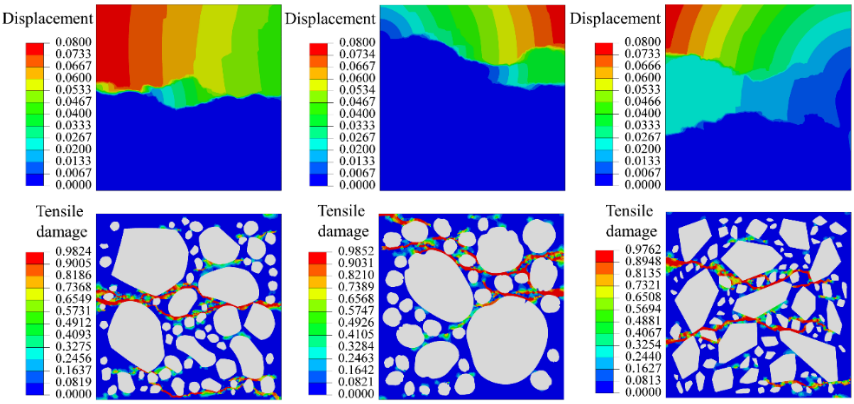
In this section, the triangular free mesh generation is conducted for the geometric model of concrete. Zero-thickness cohesive elements are embedded at the junction between aggregate and mortar, the aggregate and mortar are simulated using CPS3 (triangular elements of three-node plane stress), and cohesion elements are defined as COH2D4 (four-node 2D cohesive elements). Given the high strength of aggregates, aggregates will generally not be damaged in ordinary concrete, and thus the aggregate is assumed to be linear elastic material, the damage and fracture of mortar under external loads are simulated using the CDP model in ABAQUS, and the mechanical behavior of cohesive elements in the interfacial transition zone is simulated via a bilinear constitutive model. The material parameters[4] of each phase of concrete are listed in Table 1.

Table 1. Material parameters.

	Elastic modulus (MPa)	Poisson's ratio	Normal stiffness (MPa / mm)	Tensile strength (MPa)	Compressive strength (MPa)	Fracture energy (N / mm)
Aggregate	55400	0.16	——	——	——	——
Mortar	25700	0.22	——	3.17	37.3	——
Interface	——	——	1.4×10^6	3.01	——	0.1

4 RESULTS AND ANALYSIS

In this section, the meso-models of concrete specimens with three kinds of differently shaped (gravel, pebble, and convex polygon) aggregates are constructed, with the aggregate content remaining at 50%. Fixed constraints are applied to the bottom of each concrete specimen, while no constraints are applied at two sides, and the reference point-specimen top coupling constraint is adopted. In addition, displacement loads are applied on the reference point, followed by the static computational analysis via the ABAQUS implicit solver. Based on the extracted damage nephogram, displacement nephogram, and relevant data, the damage and failure modes and macro-mechanical properties of concrete specimens under uniaxial tension conditions are systematically analyzed.



a) Gravel aggregate b) Pebble aggregate c) Convex polygonal aggregate

Fig. 2. Comparison charts of failure modes of concrete specimens with three aggregate types in case of uniaxial tension.

According to Figure 2, for the concrete specimens with three different types of aggregates, microcracks are all initially produced in the interfacial transition zone, which gradually propagate to the mortar zone as loading continues and finally form a straight-through crack in the whole specimen. In other words, the concrete specimens with three different types of aggregates are similar in the failure mode, which basically coincided with the test results. However, microcracks are generated at different positions due to the differences in the aggregate shape and distribution and propagate to the mortar zone through different paths along the interfacial transition zone by bypassing the aggregate, resulting in great differences in the specific cracking position and the final failure mode of concrete specimens. This reflected that the crack generation is also affected, to some extent, by the aggregate distribution, so in the preparation process, concrete should be fully mixed and evenly stirred with cement mortar. In this way, the aggregate could be distributed as evenly as possible in cement mortar, give full play to the inhibition of crack expansion of aggregate, so that the concrete in the bearing can be more fully play out its comprehensive performance, to avoid local damage to affect the overall quality of the concrete project.

Figure 3 exhibits the stress-strain curves of concrete specimens with gravel, pebble, and convex polygonal aggregates under uniaxial tension as well as the relationships of their elastic modulus and tensile strength with the aggregate shape. It could be seen from the figure that in the stress-strain curves of concrete specimens with three aggregate types, the stress-strain curve of the gravel aggregate concrete specimen was steeper in both ascent stage and descent stage, where the tensile strength of gravel, pebble and convex polygonal aggregate specimens was 2.85, 2.82, and 2.80 MPa, respectively, and their elastic modulus was 36.57, 36.03, and 34.59 GPa, respectively. Among the three aggregate shapes, the gravel aggregate concrete specimen showed the highest tensile strength and elastic modulus, successively followed by the pebble aggregate concrete specimen and the convex polygonal concrete specimen. The tensile strength and elastic modulus of the gravel aggregate concrete specimens were 1.9% and 5.7% higher than those of the convex polygonal aggregate concrete specimens. This is because the surface of the gravel aggregate is more irregular and rougher with a strong embedding action on mortar and the greater occlusal force with mortar, which contributed to the highest tensile strength and elastic modulus of the gravel aggregate concrete specimen. Although the pebble aggregate was the most approximate to the elliptic shape, it was concave-convex on many parts of the surface due to the expansion deformation, while the surface of the convex polygonal aggregate was relatively smooth with the relatively weak embedding action on mortar and many edges and sharp corners so that stress concentration could be more easily generated at the junction between aggregate and mortar and the mechanical property of this concrete specimen was the weakest. Based on the above discussion, this paper concludes that the roughness of the aggregate surface has a significant effect on the tensile properties of concrete specimens, and the rougher the aggregate surface is and the fewer the sharp corners at the edges, the higher the tensile strength of the concrete. Therefore, as stated in the concrete related specifications, spherical aggregates should be optimal in the preparation of concrete.

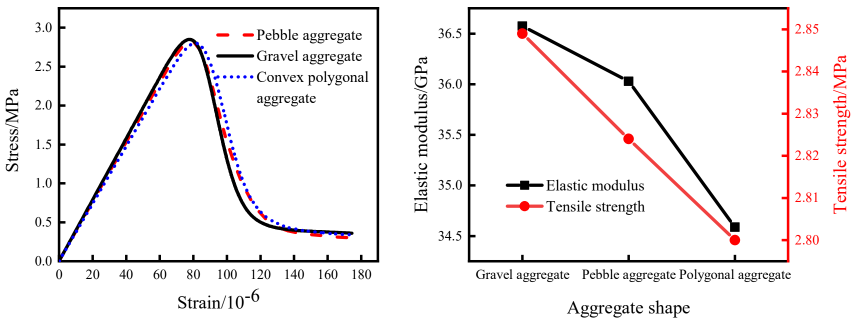


Fig. 3. Stress-strain curve charts under uniaxial tension and relationships of elastic modulus and tensile strength with aggregate shape.

5 CONCLUSIONS

In this study, the basic expansion factor function of the curvilinear parameter equation is defined, the aggregate deformation generation program is compiled via MATLAB, and the meso-numerical models of concrete with three graded irregular aggregate shapes are established and imported into ABAQUS software to simulate the uniaxial tensile failure of concrete specimens. Finally, the following conclusions are drawn:

(1) Based on the geometric models of concrete with irregular aggregates, the damage, and failure of mortar are described constitutively using the plastic damage of concrete, and cohesive elements are embedded at the junction between aggregate and mortar to characterize the mechanical behavior of the interfacial transition zone. The results show that the numerical models established in this study are highly reliable, and from the angle of data, this reflects that the aggregate shape significantly affects the mechanical properties and failure mode of concrete. Moreover, the meso-numerical simulation accuracy of concrete is improved from the perspective of geometry.

(2) During uniaxial tension, cracks first appear in the interfacial transition zone with the weakest mechanical properties. With the increase of the load, cracks gradually propagate to the mortar zone, eventually forming a straight-through crack and resulting in the fracture failure of concrete specimens. Judging from the stress-strain curves, the mechanical properties of concrete are influenced by the roughness of the aggregate surface: the rougher the aggregate surface is, the higher the tensile strength of concrete specimens are.

(3) The rationality of the aggregate shape requirements specified in relevant concrete construction codes is verified from the angle of numerical tests. In the process of concrete preparation, spherical aggregates with rough surfaces should be chosen, which is beneficial for establishing the effective cementing action between aggregate and mortar. The development of cracks is influenced significantly by the shape and position of aggregates, so the aggregate should be evenly mixed with cement mortar at a reasonable mix proportion to enhance the comprehensive mechanical properties of concrete.

Therefore, the damage and failure of concrete under uniaxial tension can be effectively described by the meso-numerical models with irregular aggregate shapes established using the expansion factor function in this study. However, the study in this paper is based on two-dimensional assumptions without three-dimensional modelling, so on the basis of this paper, subsequent studies can establish a three-dimensional model to discuss the effect of aggregate shape on the tensile properties of concrete.

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