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Damage and failure of concrete based on material mechanics

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Abstract. The failure of concrete materials and structures is caused by the damage evolution of meso-scale and macro-scale. To solve this problem, we analyzed the failure process of concrete structure caused by meso-scale crack propagation. The numerical simulation results show that the crack initiation occurred at the initial crack tip and gradually formed the main crack. Also, the results show that the nominal strength decreases with the increase of sample size. The fracture energy increases and the dispersion of the macroscopic mechanical properties decreases. We concluded that the linear elastic fracture mechanics theory can be used to analyze. In addition, the validity of the numerical analysis method and the meso-multi-crack model is verified.

Key words. Concrete, meso-cracks, failure.

1. Introduction

Concrete is a composite material composed of cement mortar matrix, aggregate and the interface between them. It has the characteristics of multiphase, heterogeneity and quasi brittleness. As an important engineering material, concrete is widely used in the construction of roads, bridges, dams, airports, tunnels and slopes and other public infrastructure and housing and other civilian facilities. However, the damage caused by the deterioration of the material properties of concrete structures often leads to immeasurable losses to the lives and property of the people [1].

In the analysis of concrete material and structure design, it is generally used as a uniform solid at the macro scale. However, in the analysis of the material properties, it is necessary to consider the discontinuity between the heterogeneous materials. The discontinuity of the micro scale is initially manifested as the initial damage state of the concrete formed by the meso-crack distribution. After the damage evolution process characterized by meso-crack coalescence (including fusion and crossover), it is shown as the discontinuity of macroscopic scale at last, that is, the generation of macroscopic crack. Therefore, the failure of concrete material is caused by the initiation of meso-cracks in concrete [2]. In addition, the propagation of fine lines,

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coalescence and macroscopic cracks will aggravate the damage of concrete in the process of cross scale evolution.

According to the different levels of failure behavior, the failure of concrete can be divided into three levels such as material, component and structure. The starting point of the effect is the initiation of the micro defects in the material, and the end point is the destruction of all levels. Generally, the failure analysis of concrete material is based on meso-scale, and the failure analysis is based on the macro scale. The failure analysis of components can choose different research scales based on the research objectives. In this way, the method of adopting different research scales for different structural levels meets the needs of engineering practice to a certain extent. However, the characteristics of the cross-scale evolution of concrete damage are ignored. It is difficult to describe the micro crack propagation in concrete, which leads to the deterioration of the performance of the macro components or structures [3]. Due to the failure of evolution, the meso-damage characteristics of concrete damage are restricted to the macroscopic property or may significantly affect the macroscopic properties. However, it is not clear how the micro structure, the material properties and the state of the phase affect the macroscopic properties of concrete under any conditions [4]. Although there is no uniform definition of the scale of the research, the solution of these problems is very important for the design of concrete and concrete structures.

2. Numerical simulation of damage and failure of three-point bending beam

The structure and loading conditions of the three-point bending beam are relatively simple, which is one of the most commonly-used tensile (I Type) fracture specimens. In this section, based on the meso-crack model, the heterogeneity of concrete material is considered. The damage and failure of concrete beams with initial crack and without initial macro crack are simulated. This paper discusses the process of component failure caused by the damage evolution, and presents a multiscale simulation method for the damage evolution process.

2.1. Failure simulation of damage evolution of concrete beams with initial cracks

In order to study the macroscopic fracture phenomenon of concrete members, one or two prefabricated cracks (usually more than 50 mm) should be prepared in the specimens, which can ensure that the fracture begins to expand from the tip of the crack. Bazant and Pfeiffier are selected to study the effect of concrete fracture size on concrete three-point bending beam specimens, and the plane stress problem is simplified [5]. The plane size of the numerical specimen is 800 mm×200 mm ($L \times H$). The initial macroscopic crack length in the middle of the beam is $a_o = 50$ mm, the relative crack depth is $a_o/H = 0.25$. There is concentrated load F in the middle of the span of the beam. The proposed method can successfully simulate the failure process of concrete beam specimens subjected to the failure of different scales. As shown in Fig. 1, its upper part represents the load and midspan displacement curve ($F - d$). Figure 1, bottom part, represents the load crack tip opening displacement curve (F – CMOD) of the specimen.

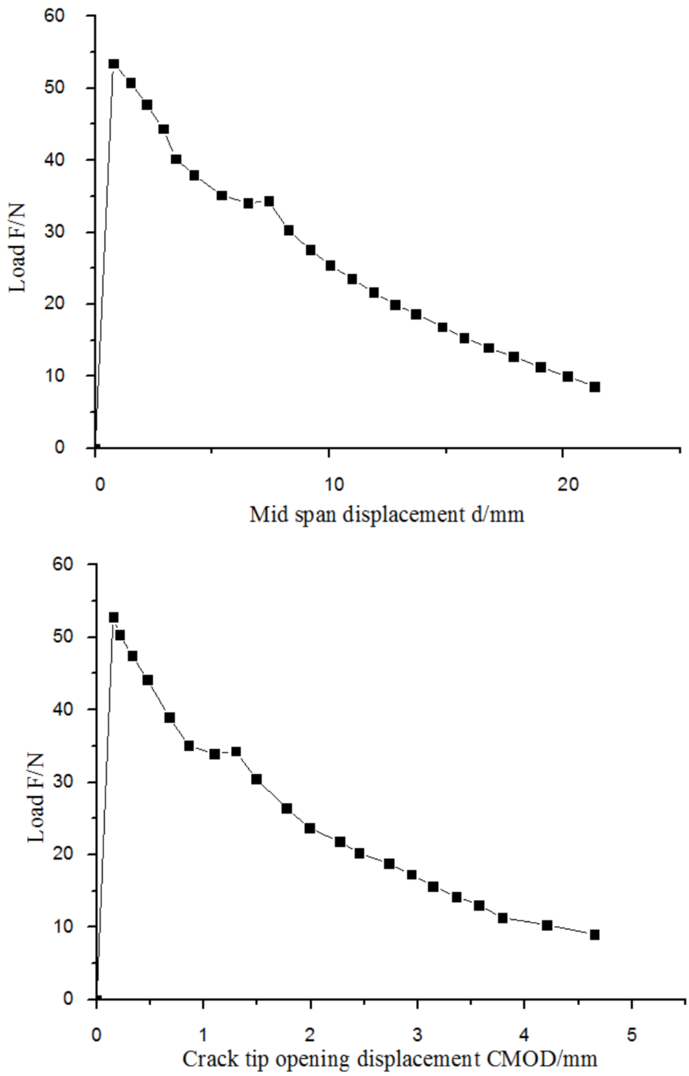

Fig. 1. Load displacement curve and load crack opening displacement curve of concrete beam specimen: upper part–load displacement curve, bottom part–load crack opening displacement curve

In this paper, the linear elastic fracture mechanics is used to judge the crack propagation, and it is assumed that the crack propagation is closely related to the damage of the meso-scopic element. Therefore, it can be seen from the figure that the unit at the beginning of the initial crack tip is damaged at the initial stage of the stress, At the same time, the $F - d$ curve and the F – CMOD curve keep a good linearity, that is, the initial failure of the concrete samples with initial macro cracks have obvious brittleness. The specimen will soon reach the peak load with the gradual evolution of the damage. At the beginning of the macroscopic crack tip, a meso-unit first appears tensile damage, which marks the beginning of crack propagation [6]. After that, the damage began to accelerate, and the crack initiation occurred at the initial crack tip and gradually formed the main crack. Damage evolution enters the macro level from the meso-level, and the sample enters the unstable stage.

2.2. Failure simulation of damage evolution of concrete beams with initial cracks

Based on the study of the upper section, the characteristics of damage evolution and crack propagation of three-point bending beam with initial macroscopic crack and its influence on the mechanical properties of the specimens were studied. The main crack is obtained by the initial crack propagation. Because the failure process of concrete is random, the position and shape of the main crack are uncertain [7]. As for the practical engineering, the study on the specimens without initial macroscopic crack should be more practical.

In order to investigate the general situation, the numerical analysis of the damage and failure of concrete beam without initial macro crack is carried out by using the concrete meso-crack model. The samples are similar to the upper section in concrete mix proportion, aggregate gradation and meso-mechanical parameters. The same method can be used to simulate the failure process caused by the cross-scale evolution of the specimens [8]. As shown in Fig. 2, it represents the load displacement curve $(F-d)$. Because the concrete sample does not contain the prefabricated crack, there is no crack opening displacement data, that is, so-called F – CMOD curve.

As shown in Fig. 2, the meso-unit at the interface is subject to tensile damage in the early stage of concrete beams, and the meso-scopic crack begins to expand along the interface. The nonlinearity of the F-d curve is not very obvious at this time. An extended interface crack reaches a certain number before peak load and begins to expand into the mortar matrix. The evolution of the crack mainly comes from the damage of the meso-scopic element in the mortar matrix and $F - d$ exhibits a certain nonlinearity. After reaching the peak load, the fusion and intersection of the local micro cracks will occur. The main crack was formed in the specimen, and the evolution of damage evolves from micro level to macro level. The sample began to enter the unstable stage and the bearing capacity decreased.

3. Analysis of the size effect of concrete beams caused by the damage evolution

The size effect of concrete members is that the experimental side value of strength, toughness and other mechanical parameters have a regular change with the increase of specimen size. The mechanical parameters obtained from the concrete test not

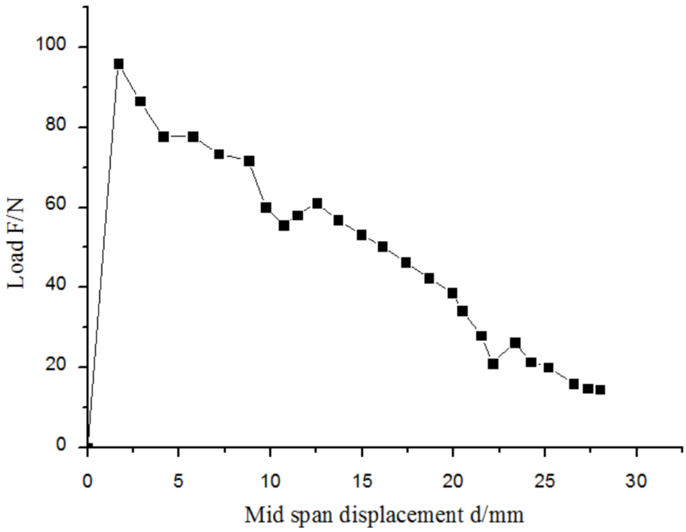

Fig. 2. Load mid-span displacement curve of concrete beam specimen

only depend on the performance of concrete, but also the size of the sample. For a long time, the size effect of concrete has been an obstacle to the design of concrete structures, life prediction and structural failure analysis. There has been a lot of work around this problem, such as Weibull statistical theory, energy release theory, fractal theory and so on. But the problem has not been completely resolved. In particular, the mechanism of concrete size effect has not been clearly understood and described.

3.1. Numerical test of size effect of concrete beam

The height of the concrete beam specimen is H (it is the characteristic size of the structure), and the length is $L = 4H$. The three-point bending load is adopted, and the load is F. In order to study the size effect of concrete materials, 5 kinds of specimens with H of 50 mm, 70 mm, 100 mm, 140 mm, and 200 mm were selected in this paper. The physical model of the concrete specimen of each size is randomly placed by the aggregate, and 7 samples of the same size are generated.

Based on the optimized numerical analysis method, the multi-scale modeling of concrete members is carried out, which can simulate the whole process of concrete beam failure. Figure 3 shows the failure mode of a concrete beam with a size of $H = 50$ mm and $H = 200$ mm. The results of the numerical simulation of each step can be used to obtain the load and displacement curves of the concrete. It includes linear phase, nonlinear strengthening stage and softening stage. As shown in both parts of Fig. 3, a–d is the representative point of the initial state of the sample, the limit of reinforcement, the softening stage and the failure state.

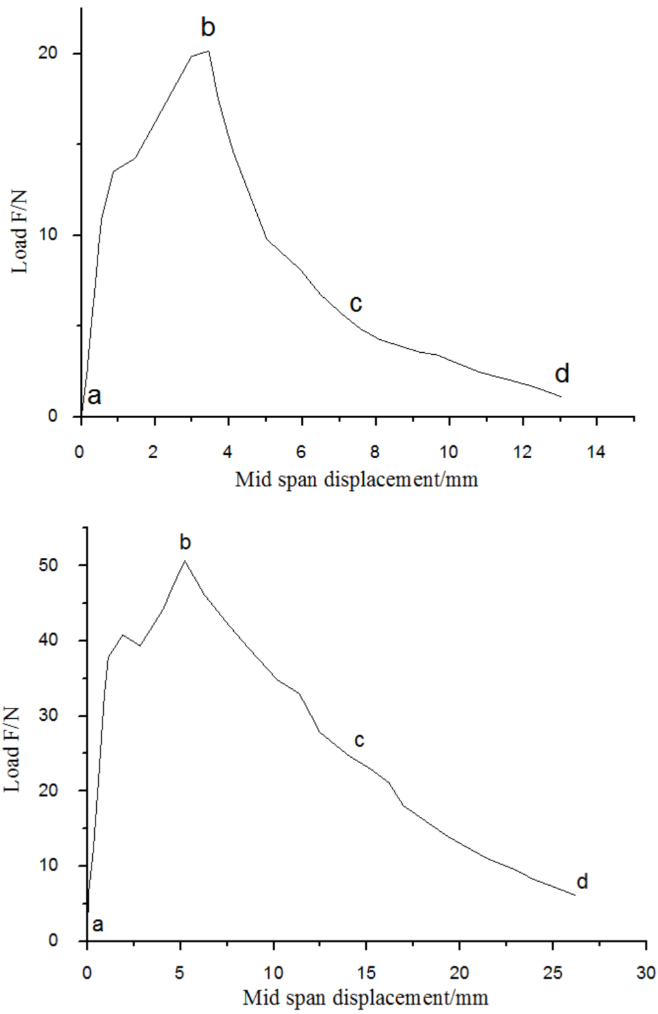

Fig. 3. Load mid span displacement curve of concrete beam: up–$H = 50\,\mathrm{mm}$, bottom–$H = 200\,\mathrm{mm}$

3.2. *Numerical results analysis*

The $F - d$ curves of the 7 samples of the same size were collected and fitted, and the fitting curve was obtained as shown in Fig. 4. It is used to represent the bending failure characteristic curve of the specimen.

In order to analyze the size effect of concrete structures, it is necessary to calculate the mechanical parameters of different sizes, including strength, fracture energy and so on. The maximum stress of concrete beam in this paper is:

$$\sigma_N = 6F/bN\,. \tag{1}$$

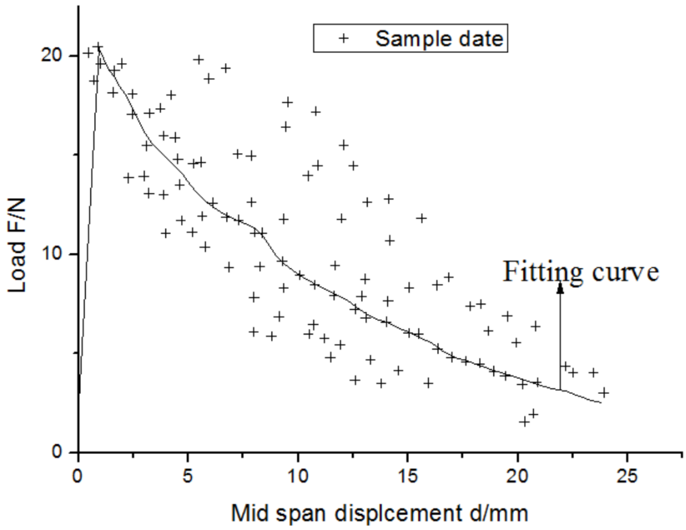

Fig. 4. Tensile fitting curve of 7 concrete beams in $H = 50\,\mathrm{mm}$

In formula (1), b is the thickness of the beam (plane strain state, $b = 1\,\mathrm{mm}$). Let d be the mid span displacement of the beam. The relative deflection of the sample is then

$$W = d/N\,. \tag{2}$$

Based on the load displacement curve in figure 4, the curves of the maximum stress (strength) and relative deflection of concrete beams with different sizes are obtained. As can be seen from the figure, the strength of the concrete beam decreases with the increase of the size, which indicates that the damage can lead to the size effect. In addition, the size effect also affects the post peak curve. When the small structure is destroyed, the relative deflection of the structure is larger. For larger structures, there are abrupt changes and jumps in the peak curve, and the relative deflection is smaller when the final failure occurs. The results of numerical simulation are summarized, and the maximum stress, the standard deviation of mid span stress and the fracture energy of concrete specimens with different sizes are obtained. As can be seen from Table 1, there is a size effect on the mechanical properties of concrete members due to the damage evolution. It shows that the strength of concrete specimens and the dispersion of the stress data in the mid span decrease with the increase of size. In addition, the fracture energy will increase.

Table 1. The size effect of the maximum stress and fracture energy

Sample size (mm)	50	70	100	140	200
Mid span maximum stress (MPa)	2.86	2.58	2.40	2.34	2.27
Mid span stress standard deviation	0.51	0.29	0.31	0.19	0.14
Fracture capacity (kJ/m)	2.41	3.14	3.51	5.22	9.11

3.3. Results

In this paper, the failure of concrete component is taken as the research focus, and the three-point bending beam of concrete is selected as the research object. The numerical analysis method and the multiple crack model are optimized and improved, and failure analysis of components caused by damage evolution is carried out. Therefore, the numerical simulation of three point bending of concrete beam with initial macro crack and without initial macro crack is carried out, while the failure process caused by the damage of the cross-scale evolution was investigated. On the basis of this, a multiscale simulation method is proposed to simulate the damage evolution process. And then the scale effect of concrete beams with different sizes is studied and the size effect and mechanism of the damage evolution are discussed. In addition, based on the fatigue failure mechanism of concrete, the multi-crack model is improved. Numerical simulation of fatigue damage of concrete beam is carried out, which analyses the fatigue damage accumulation caused by the damage evolution and gives the prediction method of fatigue life. The main research work and results are summarized as follows:

(1) The failure process of concrete beam subjected to the failure of the concrete beam with initial macro crack and without initial macroscopic crack is simulated. The results show that the concrete beam with initial macro crack has obvious brittleness. The damage evolution is mainly focused on the initial macroscopic crack tip, and the final main crack is obtained from the initial macroscopic crack propagation.

(2) 5 kinds of concrete beam specimens with different sizes were selected by using the optimized numerical analysis method, and each sample was made of 7 samples. The numerical experiments on the size effect of concrete members are carried out, and the mechanism of the size effect of concrete is discussed from the perspective of the evolution of damage. The results show that the nominal strength decreases with the increase of sample size. The fracture energy increases and the dispersion of the macroscopic mechanical properties decreases.

4. Conclusion

In this paper, the failure mechanism of concrete materials used in engineering is studied, and the characteristics of concrete damage and failure are analyzed. This paper mainly introduces the theory and method of concrete fracture mechanics analysis, the theory and method of concrete damage mechanics analysis. Based on the analysis of the existing methods of meso-numerical analysis of concrete, the meso-crack model is chosen as the research tool in this paper.

The failure process of concrete induced by the meso scale damage evolution is calculated and analyzed by using meso-crack model. Based on the analysis of the meso-characteristics of concrete materials, the concrete material is idealized and induced to some degree. Meanwhile, the meso-crack model of concrete is established and the reasonable model parameters are selected. The numerical simulation technique is used to simulate the failure process of concrete. Based on the verification of the effectiveness of the multi-crack model, the damage evolution process is quantitatively analyzed by using the damage mechanics analysis method. The relationship between macro and meso-damage variables of concrete material is discussed. The numerical simulation of uniaxial tensile tests of concrete specimens with different mixing ratios was carried out. The influence of damage on the macro mechanical properties of concrete was studied. It is proved that the linear elastic fracture mechanics theory can be used to analyze. In addition, the validity of the numerical analysis method and the meso-multi-crack model is verified.

References

[1] B. Sun, Z. Li: *Adaptive multi-grid FE simulation on dynamic damage and seismic failure of concrete structures.* Journal of Vibroengineering *18* (2016), No. 1, 276–288.

[2] R. Guo, S. Li, D. Zhou: *The three-stage model based on strain strength distribution for the tensile failure process of rock and concrete materials.* Acta Mechanica Solida Sinica *29* (2016), No. 5, 514–526.

[3] X. Gu, Q. Zhang, D. Huang, Y. Yv: *Wave dispersion analysis and simulation method for concrete SHPB test in peridynamics.* Engineering Fracture Mechanics *160* (2016), 124–137.

[4] C. Ma, W. Z. Chen, J. Y. Sun: *Numerical implementation of spatial elastoplastic damage model of concrete in the framework of isogeometric analysis approach.* Mathematical Problems in Engineering (2016), paper 4273024, 13 pages.

[5] F. Safaei, C. Castorena, Y. R. Kim: *Linking asphalt binder fatigue to asphalt mixture fatigue performance using viscoelastic continuum damage modeling.* Mechanics of Time-Dependent Materials *20* (2016), No. 3, 1–25.

[6] Z. Yu, S. Li, D. Lu, C. Lu, J. Liu: *FFailure mechanism of single-layer steel reticular domes with reinforced concrete substructure subjected to severe earthquakes.* International Journal of Steel Structures *20* (2016), No. 4, 1083–1094.

[7] M. Luković, B. Šavija, E. Schlangen, G. Ye, K. van Breugel: *A 3D lattice modelling study of drying shrinkage damage in concrete repair systems.* Materials (Basel) *9* (2014), No. 7, 575.

[8] C. Qian, Y. Nie, T. Cao: *Sulphate attack-induced damage and micro-mechanical properties of concrete characterized by nano-indentation coupled with X-ray computed tomography.* Structural Concrete *17* (2016), No. 1, 96–104.

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