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MESOSCALE NUMERICAL STUDY OF AGGREGATE SIZE IN CONCRETE BY DISCRETE ELEMENT METHOD

RAN ZHU [*], SYED YASIR ALAM [*] AND AHMED LOUKILI [*]

[*] * GeM Institute, École Centrale de Nantes/Université de Nantes/CNRS
1 rue de la Noë, 44321 Nantes, France
e-mail: {ran.zhu ; Syed-Yasir.Alam ; Ahmed.Loukili}@ec-nantes.fr

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Abstract: A local crack opening displacement softening model is developed in the framework of discrete element method in order to investigate the fracture behaviour of concrete with different aggregate size. The results showed that the proposed model can be used for numerical analysis of concrete fracture and the zone of fracture process zone can be visualized.

1 INTRODUCTION

Concrete is a typical quasi-brittle material. Compared with those materials, its mechanical behaviours and rupture processes are so complicated. So the microstructure features of concrete such as aggregate size, shape and volume fraction have certain effects on its macroscopic mechanisms, as it leads to the development of a microcracking zone which causes large energy dissipation. Macroscopic mechanical models explicitly take into account the nonlinear zone where the microcracking occurs. The local fracture characteristics cannot be captured.

In this study, numerical investigation of concrete behaviour at meso-scale (three-phase composite, i.e. matrix, interface, and aggregate) is performed by using Discrete Element Modelling (DEM). Compared with FEM, DEM looks into micromechanics of the problem and allows a grain level control and can solve discontinuous problem. In the existing literature by using modelling code DEM, parallel bond model [1-2] or contact bond model [3-4] are the mostly used contact models. These investigations are often focused on a specific mechanical behaviour of concrete and mainly paid more attention to the mechanical response only up to the peak load. In order to solve the problems that remained by using linear elastic model, a softening contact bond model based on the work of Liu et al. [5] is inserted in the framework of the discrete element method. The effects of aggregate size on the behaviour of concrete on the fracture process are shown. DEM results at the global level are compared with the corresponding experiments. Through a comparison between numerical and experimental results, it can be demonstrated that the proposed model can be used for numerical analysis of quasi-brittle materials like concrete and the fracture process zone can also be displayed visibly.

2 DISPLACEMENT SOFTENING MODEL

The particle elements are assumed either rigid discs in 2D or rigid spheroids in 3D. These particles can overlap or detach, when the system is subjected to mechanical actions. The concept of DEM is based on the translational and rotational movement of particles due to forces and moments which act at the contact point between the particles.

While the micro-parameters of insert contact bond model in DEM could not satisfy the compressive strength and tensile strength simultaneously. Potyondy [6] and Schopfer [7] showed that when the model is calibrated to match the UCS experiment of rock, the tensile strength of rock is significantly overestimated. The reason is that the tensile strength and compressive strength are increased with the increase of bond tensile strength ($\overline{\sigma}_c$). While for the brittle materials like rock and concrete, the compressive strength is about one order of magnitude lager than tensile strength. As a result, the micro parameter $\overline{\sigma}_c$ for compressive strength is also about one order of magnitude larger than tensile strength. Therefore, the parallel bond model inserts in DEM is no longer suitable for the simulation of brittle, like rock and concrete. So in this paper, a softening contact bond model based on the work of Liu et al. [5] is introduced to model the post-peak behaviours of concrete. Previous researchers [8-9] have proposed some implementations of softening bonds to model the quasi-brittle materials, but most of them are linear softening models. Here, an exponential softening model is developed which better represents the cementitious material behaviour [10]. In continuum modelling, the relationship between tractions and relative displacements of two virtual surfaces in the fracture process zone is determined by the softening laws [11-12]. The concept is applied to DEM modelling by defining the fracture process zone as an area containing inter-particle bonds undergoing failure. A relationship between stress σ (σ_n, σ_s) in each bonding contact and the relative displacement u (u_n, u_s) of the corresponding interaction pairs are established. The elastic exponential softening model is presented in Figure 1.

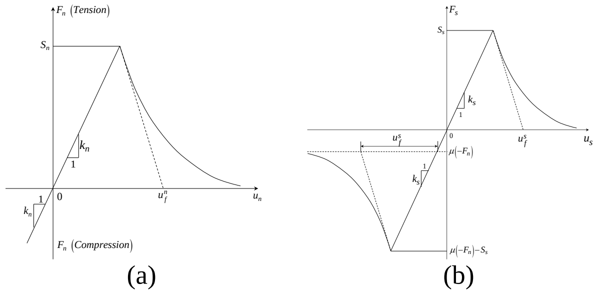

(a) (b)

Figure 1: Constitutive behaviour of contact displacement-softening model: (a) normal behaviour; (b) shear behaviour

Based on the previous studies, an elliptical failure envelope is adopted here and the equation is given below.

$$\left(\frac{F_n}{S_n}\right)^2 + \left(\frac{F_s}{S_s}\right)^2 = 1 \tag{1}$$

When the yield surface is reached, the bond strength follows the softening path rather than decrease to zero directly. It decreases according to a damage law which is proposed by Jirásek and Bauer [13]. The damage parameter in normal and shear directions have the same value. It means that there is only one damage parameter (D_f), which is widely accepted in quasi-brittle materials modelling [14-15].

$$D_f = \max(D_f^n, D_f^s) = \begin{cases} 0 & u_{n,s} \le u_e^{n,s} \\ 1 - \dfrac{u_e^{n,s}}{u_{n,s}} \exp\left(-\dfrac{u_{n,s} - u_e^{n,s}}{u_f^{n,s} - u_e^{n,s}}\right) & u_{n,s} > u_e^{n,s} \end{cases} \tag{2}$$

Where $u_{n,s}$ is the relative normal or shear displacement between two particles; $u_e^{n,s}$ is the displacement corresponding to elastic limit in normal or shear direction; $u_f^{n,s}$ is the parameter which controls the slope of softening curve in normal or shear direction.

The equation for calculating the bond force in normal or shear direction is given below.

$$F_{n,s} = \left(1 - D_f\right) k_{n,s} u_{n,s} = \begin{cases} k_{n,s} u_{n,s} & u_{n,s} \le u_e^{n,s} \\ k_{n,s} u_e^{n,s} \exp\left(-\dfrac{u_{n,s} - u_e^{n,s}}{u_f^{n,s} - u_e^{n,s}}\right) & u_{n,s} > u_e^{n,s} \end{cases} \tag{3}$$

Then, at a certain damage condition, the reduced normal strength and shear strength are calculated by the equations as follows.

$$
\begin{aligned}
S_{n,sof} &= \left(1-D_f\right) k_n u_n \\
S_{s,sof} &= \left(1-D_f\right) k_s u_s
\end{aligned}
\tag{4}
$$

Bond fails either in tension or shear, and when the particles are in compression, shear strength is augmented by the slip which is contributed by compression.

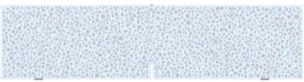
$$
S'_{s,sof} = \mu\left\langle -F_n \right\rangle + S_{s,sof} \tag{5}
$$

Where $\langle \cdot \rangle$ is Macaulay brackets; $S_{s,sof}$ is the softened shear strength.

Thus, the softening model is established by the above equations. The bond behaviour of softening model is controlled by μ ; S_n and S_s ; k_n and k_s ; u_f^n and u_f^s .

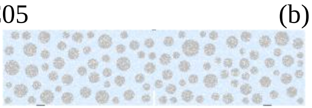
3 STUDY OF AGGREGATE GRAIN SIZE EFFECT

In order to perform the scaling of d_a, three types of concrete mix are designed ($C05$, $C10$, and $C20$) with the same aggregate to mortar volumetric ratio and same mortar properties, only the aggregate sizes are changed. The specimens used for modelling for can be found in Figure 2.



(a) C05

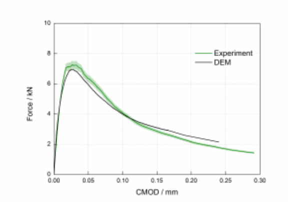
(b) C10



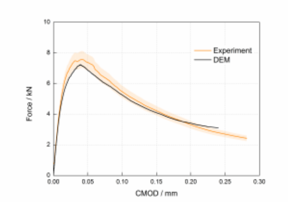
(c) C20

Figure 2: Specimens for each concrete series

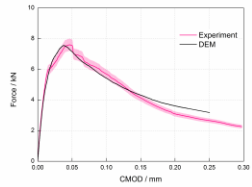
The Force-CMOD curves for each concrete series are illustrated in Figure 3.



(a) C05



(b) C10



(c) C20

Figure 3: Comparison between experimental and numerical Force-CMOD curves for different concrete

The Force-CMOD curves obtained by simulation match well with the experimental curves. There is a little deviation at the end of the curves which can be explained due to the boundary effect. The softening model used in this study, the fracture energy is constant along the ligament length.

From the Figure 3, it can also be observed that with the load increases, all the specimens experience three stages, namely linear elastic at the beginning, hardening until reaching the peak force and softening until the totally failure. Then the fracture path for each DEM concrete series was studied. Figure 4 presents fracture paths for each DEM concrete series at 60% of the maximum force.

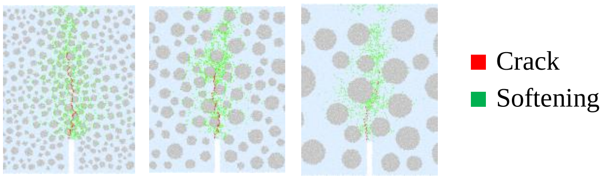


Figure 4: Specimens for each concrete series

The roughness of the fracture path increases as the aggregate size increases (Figure 4). Overall, the fractures tend to follow the weakest part of concrete, namely interface transition zone (ITZ). More aggregates are placed at the crack path for concrete with smaller aggregate. It means that there exists more ITZs compared with concrete with larger concrete and it is easier to form the crack path. The lower mechanical strengths of ITZs decrease the loading capacity of concrete beam. So, the loading capacity of $C05$ is smaller than $C20$.

4 CONCLUSIONS

In order to investigate the influence of the maximum aggregate on the FPZ length and the post-peak behaviours of concrete, a crack opening displacement softening model is developed. Through a comparison between numerical and experimental results, it can be shown that the proposed model can be used for numerical analysis of concrete.

REFERENCES

[1] Lian, C., Zhuge, Y. and Beecham, S., 2011. Numerical simulation of the mechanical behaviour of porous concrete. *Engineering Computations.* **28**(8):984-1002.

[2] Zhou, S., Zhu, H., Yan, Z., Ju, J. W. and Zhang, L., 2016. A micromechanical study of the breakage mechanism of microcapsules in concrete using PFC2D. *Construction and Building Materials*. **115**: 452-463.

[3] Elkadi, A. S. K., 2005. Fracture scaling of concrete under multiaxial compression. *PhD Thesis*, Delft University of Technology, the Netherlands.

[4] Qin C, and Zhang C., 2011. Numerical study of dynamic behavior of concrete by mesoscale particle element modeling. *International Journal of Impact Engineering*. **12**(38):1011-1021.

[5] Liu H. Z., Lin J. S., He J. D., and Xie H. Q., 2018. Discrete elements and size effects. *Engineering fracture mechanics*. **189**: 246-272.

[6] Potyondy, D. O. and Cundall, P. A., 2014. A bonded-particle model for rock. *International journal of rock mechanics and mining sciences*. **41**(8): 1329-1364.

[7] Schöpfer, M. P., Abe, S., Childs, C. and Walsh, J. J., 2009. The impact of porosity and crack density on the elasticity, strength and friction of cohesive granular materials: insights from DEM modelling. *International journal of rock mechanics and mining sciences*. **46**(2):250-261.

[8] Camborde F., Mariotti C., and Donzé F., 2000. Numerical study of rock and concrete behaviour by discrete element modelling. *Computers and Geotechnics*. **27**:225-247.

[9] Galouei M. and Fakhimi A., 2015. Size effect, material ductility and shape of fracture process zone in quasi-brittle materials. *Computers and Geotechnics*. **65**:126-135.

[10] Reinhardt H. W., Cornelissen H. A., and Hordijk D. A., 1986. Tensile tests and failure analysis of concrete. *Journal of Structural Engineering*. **112**:2462-2477.

[11] Dugdale D. S., 1960. Yielding of steel sheets containing slits. *Journal of the Mechanics and Physics of Solids*. **8**:100-104.

[12] Barenblatt G. I., 1962. The mathematical theory of equilibrium cracks in brittle fracture. *Advances in applied mechanics*. **7**: 55-129.

[13] JiráSek M. and Bauer M., 2012. Numerical aspects of the crack band approach. *Computers & structures*. **110**: 60-78.

[14] Bobiński J. and Tejchman J., 2016. Comparison of continuous and discontinuous constitutive models to simulate concrete behaviour under mixed-mode failure conditions. *International Journal for Numerical and Analytical Methods in Geomechanics*. **40**:406-435.

[15] Cusatis G., Bažant Z. P., and Cedolin L., 2003. Confinement-shear lattice model for concrete damage in tension and compression: I. Theory. *Journal of engineering mechanics*. **129**: 1439-1448.